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LANGUAGE OF EXPERIMENT."

INTRODUCTION TO
PHYSICAL SCIENCE

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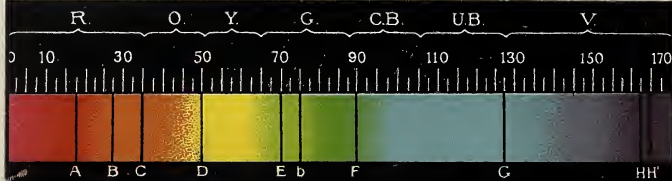
Gray Marshall

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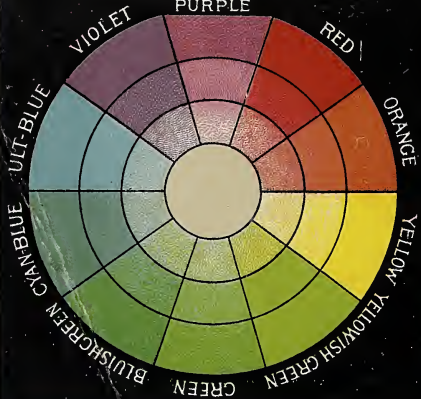
Sodium.

Lithium

Potassium.

Strontium

COMPLEMENTARY COLORS.
PURPLE



PRIMARY COLORS.



INTRODUCTION
TO
PHYSICAL SCIENCE

BY
ALFRED PAYSON GAGE, PH.D.
AUTHOR OF "PRINCIPLES OF PHYSICS,"
"ELEMENTS OF PHYSICS," ETC.

REVISED EDITION

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PREFACE

METHODS of teaching elementary physics have undergone, within scarcely more than a decade, many radical changes. The educational pendulum has vibrated between extreme methods of all text-book and no text-book, all laboratory and no laboratory, the inductive method and the deductive method, all oral instruction and little oral instruction. At present it seems to have approached the point of equilibrium where the good in each of these methods is given its due weight. It appears to be the consensus of opinion among teachers of physics that the method of instruction which includes a due proportion of text-book study, lecture-room demonstration, and individual work in the laboratory is the method conducive to the highest order of results from an educational point of view.

In revising this book, the attempt is made to emphasize its *text-book* feature. It has been the author's purpose to place before the pupil in simple language and in logical order, with due regard to child psychology, the general principles and the important laws of physical science, and not to allow them to be obscured by a multiplicity of experimental details which would be more appropriate in a teachers' handbook or in a laboratory manual. Some experiments have been introduced with a view to making the presentation of the subjects

realistic ; but they are, in the main, such as the pupil can perform, and should be encouraged to perform, by himself outside of the class hours.

Numerous practice exercises are given, from which selections may be made at the discretion of the teacher. It is generally conceded that nothing else so tends to clarify the pupil's ideas and to fix scientific principles in his mind as does the solving of problems and questions growing out of these principles. Furthermore, since acquaintance with the history of a science helps to make attractive and to humanize that which might otherwise seem dull and colorless, frequent allusions are made to the great discoveries and researches by means of which the edifice of physical science has been built up, and portraits of some of the most notable of its master-builders have been interspersed throughout the book.

Provision has been made for a year's work, on the supposition that about one third of the time will be devoted to laboratory practice. For laboratory use the teacher will choose from the many excellent manuals now available the one best adapted to his ideas and convenience. Should it seem expedient to use a manual of the same authorship as this text, he will choose between the *Physical Manual and Note Book* and the *Physical Experiments*. The latter is especially adapted to meet the requirements for admission to Harvard University.

The author desires to acknowledge especial obligations to Arthur W. Goodspeed, Ph.D., and to Clarence G. Hoag, A.M., of the University of Pennsylvania, who have read the manuscript and proof of the entire book

and furnished valuable criticisms and suggestions. His thanks are also due to Mr. Albert Perry Walker, English High School, Boston; Mr. Chester B. Curtis, High School, St. Louis; and Mr. Joseph Sparks, Superintendent of Schools, Aurora, Neb., for assistance in correcting the proof.

ALFRED PAYSON GAGE.

BOSTON, MASS., 1902.



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PHYSICAL SCIENCE

CHAPTER I

INTRODUCTION

SECTION I

DOMAIN OF PHYSICS — SOME PROPERTIES OF MATTER

1. **Physics defined.** — As we look around in the world in which we live, we receive impressions from a variety of objects independent of ourselves. Some of these objects we see, some we hear, others we feel, taste, or smell, while many appeal to several senses.

Our senses also apprise us that objects undergo many changes under varying conditions. For example, if a stick of sealing wax be rubbed with a dry flannel, it undergoes a change of state by virtue of which it attracts toward itself small pieces of paper. By the application of heat ice is changed to a liquid and even to invisible steam, and a dark gray piece of iron may become red or even white.

Any change in an object is called a *phenomenon*. Both our experience and our reason lead us to conclude that there is a *cause* for every phenomenon. Our present study chiefly relates to natural phenomena and their causes. Every one who has used his senses to

any purpose has become acquainted, even before beginning the study of our science, with a great many phenomena, among them some of the yet unexplained.

Things that affect our senses directly are called *matter*, e.g., stone, water, air, etc. It is believed that there exists something that does not affect the senses directly, something that fills all the space of the universe, called *the ether*. We shall find, as we proceed, that all changes in the appearance of objects are accompanied by *motion*. *Physics is the science which treats of matter and its motion, and of vibrations in the ether.*

2. Some Properties of Matter.—(1) *Extension and impenetrability*. Any portion of matter is called a *body*. The kind of matter of which a body is composed is spoken of as its *substance*. For example, a ball is a body; its substance may be rubber, wood, iron, etc. Every body, however small, occupies space; that is, it has the three dimensions, *length*, *width*, and *thickness*; in other words, it possesses the property of *extension*.

It is self-evident that no two bodies (e.g., our two hands) can occupy the same space at the same instant. That property of matter in virtue of which a body occupies space to the exclusion of all other bodies is called *impenetrability*.

Experiment.—Float a cork on a surface of water, cover it with a tumbler as in Fig. 1, and force the tumbler, mouth downward, deep into the water. (The cork serves merely to show the boundary surface between the water and the air.) Does water enter and fill the tumbler? What property does this experiment show air to possess? What evidence that air is matter do you discover?

Matter is defined as *that which occupies space and possesses impenetrability*. Both these properties are essential to matter. A shadow occupies space but does not possess impenetrability. Air and other gases are invisible; hence, they are not readily recognized as matter. If, however, we show that air possesses impenetrability, we have reason to believe that air is matter, since it possesses that which nothing but matter possesses.

(2) *Divisibility*. It is believed that if we should divide and subdivide a piece of matter, say a piece of marble, and the process were continued far enough, we should eventually arrive at such a condition that if the division of the excessively minute particle were continued any further, the portions would no longer possess the properties of this substance (*e.g.*, marble), but be some new kind of matter, of which this substance is built up. Hence, we suppose that for every kind of matter there exists some particle which is the smallest that can possibly exist. Such smallest particle of any substance is called a *molecule*. Molecules are much too small to be seen.¹ Their existence is inferred from phenomena which can be explained only on the supposition that they exist.

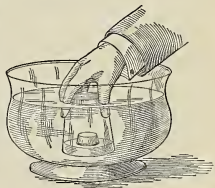


FIG. 1

(3) *Compressibility and expansibility*. All bodies are compressible and expansible, though in very different

¹ If a globe of water the size of a football 6 inches in diameter were magnified to the size of the earth, the molecules would be greater than small shot and smaller than footballs.—LORD KELVIN.

degrees. Air and gases generally are very compressible. A proof, though by no means the most convincing one, of the existence of molecules and of the granular structure of bodies may be found in this fact. Matter (*e.g.*, a body of gold or water) is either continuous as it appears to the eye, or it is discontinuous, granular, composed of distinct particles (molecules), somewhat as represented in Fig. 2. *But bodies are compressible and expansible.*

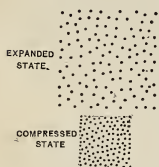


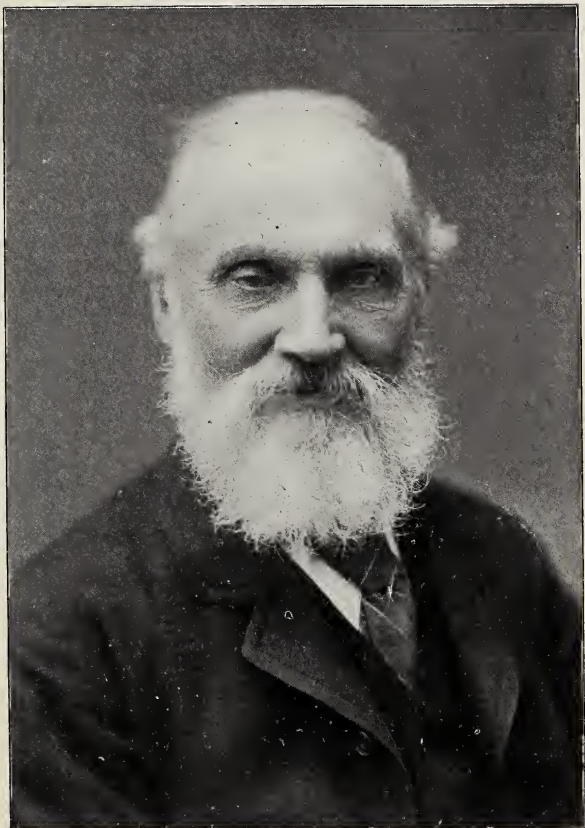
FIG. 2

On the supposition that matter is continuous these phenomena cannot be explained; but on the supposition that matter is composed of disconnected particles they are easily explainable. According to the latter supposition a change of volume by contraction or expansion means a coming together or a separation of

the molecules composing the body, as represented in Fig. 2. The property of compressibility is at once a consequence and an evidence of the molecular constitution of matter.

3. Theory of the Constitution of Matter ; Porosity. —

For reasons which will appear as our knowledge of matter is extended, physicists have generally adopted the following theory of the constitution of matter: *Every body of matter except the molecule is composed of exceedingly small disconnected particles, called molecules. The molecules are ever in a state of intense vibration, every molecule making many billions of vibrations per second. In their to-and-fro motions neighboring molecules hit and rebound from one another; hence, the molecules in a body are never in contact except at the*



LORD KELVIN (1824-

Probably the most noted of living physicists; especially renowned both for his many original researches and valuable contributions to scientific knowledge and for the invention of many electrical devices of great practical and commercial value. From a photograph.

instants of collision. When the temperature of a body rises, the molecules, moving more rapidly, strike harder blows and drive one another a little farther apart; hence, the body expands.

If the molecules of a body vibrate and are never in contact except at the instants of collision, it follows that there must be spaces between them. These spaces are called *pores*. The pores of a body are spaces within a body not filled with the substance of which the body is composed.

Even in bodies in which the molecules are most compact, such for instance as gold, it is estimated that the average distance between the molecules is many times the diameter of the molecule.

All matter is porous. Water may be forced through the pores of iron and gold. Strictly speaking, *only molecules possess the property of impenetrability*. The term *pores*, in physics, is restricted to the *invisible spaces* that separate molecules and does not include such cavities as may be seen with the naked eye in sponges, and with a microscope in wood, etc.

4. Three States of Matter ; Fluidity. — We recognize three states or conditions of matter, *viz.*, the *solid*, the *liquid*, and the *gaseous*, represented by earth, water, and air.

In solids the molecules offer resistance to change in their relative positions. Hence, solid bodies tend to preserve a definite volume and shape.

In liquids the molecules offer little resistance to change of relative position, but glide around and past one another with great freedom. A body of liquid, therefore, as we experience it on the earth, can have

no shape of its own, but on account of its weight readily takes the form of the vessel in which it may be placed.

The distinctive characteristic of a gas is its incessant struggle to occupy a greater volume, or the tendency of its molecules to separate from one another. Hence, both the volume and the shape of a body of gas are determined only by the vessel in which it is inclosed.

In consequence of the mobility of their molecules and the ease with which they *flow*, liquids and gases are called *fluids*. Susceptibility of motion of the molecules of a body around and among one another is called *fluidity*. All bodies of matter, including solids, possess this property, but in very different degrees. It is due to this property that solids can be bent, stretched, and compressed, and that most metals can be drawn into wires and rolled or hammered into sheets.

EXERCISES

1. How do you know that air is matter? *It is impenetrable.*
2. Give some reason for concluding that all matter is molecular in structure.
3. Can molecules be seen? Can pores be seen? *Yes.*
4. Whence do fish obtain the air with which their blood is aerated? *From the water.*
5. Whence come the bubbles of gas that cause the effervescence when soda water is drawn from a fountain? *From the gas dissolved in the water.*
6. What is understood by a molecule of chalk? *Smallest part of chalk.*
7. According to the definition of a molecule, can such a thing exist as a half of a molecule of chalk? *No.*
8. (a) In Experiment 1 why does not the water enter the tumbler when it is thrust down into the water? *Because of the air pressure.* (b) Does the water enter a little way into the tumbler? *Yes.* Explain. *Because of the air pressure.*

9. Explain how the flow of liquid into the bottle through the funnel *A* (Fig. 3), may be regulated by pressure on the rubber tube *B*.

10. (a) We say that a tumbler is "full of water." May we not with equal propriety say that it is at the same time full of air? (b) If the tumbler be full of both water and air at the same time, shall we say that these substances do not possess the property of impenetrability?

11. If a block of wood be placed under water in an air-tight vessel (Fig. 4), and the air be removed, air bubbles will form on the surface of the wood and also in mid water and rise to the surface of the water. What do you infer from this respecting the porosity of wood and water?

12. (a) Give names of at least three substances. (b) Give a name of a *body* of each substance named.

13. Prepare a list of (a) several atmospheric phenomena; (b) several phenomena which may occur to water; (c) several phenomena producible by heat; (d) several phenomena which may accompany cooling or loss of heat; (e) several sound phenomena; (f) several phenomena caused by light; (g) several phenomena attributable to electricity.

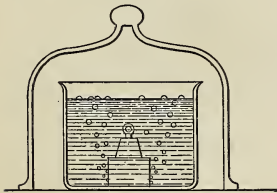


FIG. 4

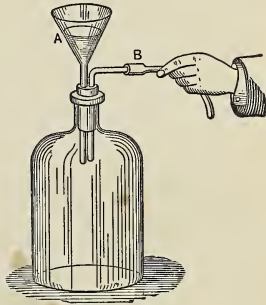


FIG. 3

14. What evidence have you that such phenomena as you have specified ever exist?

15. How may it be shown that water is porous?

16. What evidence does an air bubble in water furnish that air is matter?

SECTION II

PHYSICAL MEASUREMENTS

5. Units of Measurement. — Physics is often called a “science of measurements,” since most of the truths of which it treats are based on measurements that have been made from time to time. Measuring consists in finding how many times a definite quantity, called a *unit*, is contained in the quantity to be measured. For example, should we wish to measure the length of a table, we might choose for a unit of measurement the length of a certain pencil and proceed to find how many times this pencil may be laid along the table. If ten times, we say the table is ten pencil-lengths long.

The unit of measurement must be a definite quantity of the same kind as the thing to be measured. Thus, a unit for measuring length must be a certain length, a unit for measuring surface must be a certain quantity of surface, and a unit for measuring volume must be a definite volume. A unit which has become legalized, either by statute or by common usage, is called a *standard unit*. The *expression* of a physical quantity consists of a statement of the *concrete unit* employed, *e.g.*, pound, foot, quart, etc., with the *number of those units* prefixed. The numerical part, called the *numeric*, is obtained by measurement.

6. Metric System of Measures. — (In this connection the Table of Metric Measures, in the Appendix, should be studied, and the pupil should immediately become

familiar with metric units, particularly units of length, by practice in measuring the dimensions of familiar objects.) The term *metric* is derived from the word *meter*, which is the name of a unit employed in this system for measuring length. The international standard meter is defined by law to be the length of Borda's platinum rod at the temperature of 0° C. (32° F.). This rod, constructed by Borda, a French mathematician, about 1796, is kept at the International Bureau of Weights and Measures in Paris.

The metric system is now universally employed in scientific work. The United States government carefully preserves in Washington copies of the international meter and other metric units. These were declared by Congress (1866) to be the standard units of measurement for this country, and they are destined to supplant completely, at no distant day, the irrational and unwieldy British units.

The units of surface and volume are, respectively, surfaces and cubes whose edges are some one of the units of length, as the square centimeter (cm.^2) or the cubic centimeter (cm.^3 or cc.). For the measurement of such articles as are bought and sold by dry or liquid measure, also for the measurement of capacities of vessels, the *liter* ($= 1 \text{ dm.}^3$) is generally used.

7. Volume, Mass, Density, and Weight. — The quantity of space a body occupies is its *volume*, and is expressed in cubic centimeters, etc. By the *mass* of a body is meant the *quantity of matter* in it.

The unit of mass employed in science is the *gram*. The gram is the one-thousandth part of the standard *kilogram*. The kilogram is the mass of a certain piece

of platinum in the keeping of the French government at Paris. It is also, with considerable accuracy, represented by the mass of a cubic decimeter of pure water at the temperature of 4° C. Since a cubic decimeter contains 1000 cc., the mass of 1 cc. of water is 1 g. *A kilogram of any substance is that quantity of the substance which, placed on a scale pan, would just balance in a vacuum the standard kilogram placed on the other pan.*¹

Mass must not be confounded with weight. Mass means *matter*, weight means *force*. *The weight of a body is the measure of the force with which the body is drawn toward the earth.* This force varies at different distances above the earth and at different latitudes, while the mass of the body remains the same. Although masses of bodies and weights of bodies are quantities entirely unlike in kind, yet there exists between them, when the distances of bodies from the earth are the same, a simple relation such that we make weight the practical test of mass by assuming that two bodies have the same mass if they have the same weight. In other words, *at equal distances from the earth mass is directly proportional to weight*, and units of the same name are employed in measuring both quantities. This is one of many instances in physics in which *one quantity is indirectly measured by measuring another that is proportional to it.*

8. Density. — *Equal volumes of different substances (e.g., cork, chalk, lead) contain unequal quantities of matter.*

¹ For certain uses in physical laboratories balances are made sensitive enough to measure a hundredth of a milligram of matter. Their delicacy may be described by saying that they will measure the quantity of matter in a pencil mark.

Of two substances, that which contains the greater quantity of matter in the same volume is said to be the *denser*. The *density* of a substance is expressed by stating the *mass per unit of volume* of that substance. The density of water (at 4° C.) is 1 g. per cubic centimeter, and the density of cast iron is about 7.2 g. per cubic centimeter.

The mean, or average, density of a body is found by dividing its mass by its volume. Thus, if the mass of a body be 32 g. and its volume be 5 cc., its mean density is $(32 \div 5 =) 6.4$ g. per cubic centimeter.

EXERCISES

1. Define the following: a meter; a centimeter; a square decimeter; a cubic decimeter; a cubic centimeter; a liter; a kilogram-mass; a gram-mass.

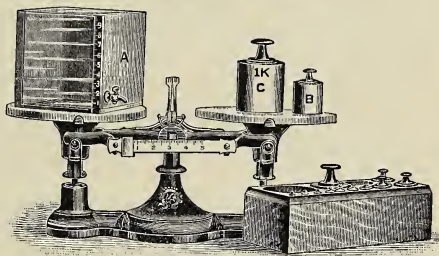


FIG. 5

2. Fig. 5 represents a trip balance much used in commerce. On one platform of the balance stands a vessel, *A*, whose capacity is 1 l., or 1 dm.³ (See Appendix.) On the other platform is a body, *B*, which just balances the vessel, *A*, when it is empty. Let another body, *C*, whose mass is 1 kg. be placed on the same platform. The

balance between the articles on the two platforms is destroyed. Let water be poured into the vessel. When it becomes just even full of water the balance is restored. (a) How does the mass of the water in *A* compare with the mass of the body *C*? (b) What mass of water does the vessel hold? (c) What volume of water does it hold? (d) What is the density of the water?

3. What is the weight of a liter of water? of 1 cc. of water? of 25 cc. of water?

4. Fifty cubic centimeters of cast iron weigh 360 g. What is the density of cast iron?

5. What is the weight of 1 dm.³ of cast iron? 3937

6. Draw a line 1 inch long. Measure its length in centimeters; in millimeters.

7. Express each of the following quantities in centimeters and find their sum: 2 dm. 4 cm.; 17 cm. 4 mm.; 27 mm.; 0.5 m.; and 4.7 cm.

8. Fig. 6 is a household article called a spring balance, used for weighing. Fig. 5 is a trip balance, also used, in common speech, for weighing. (a) Should a body in consequence of change of distance from the earth change in weight, which of these two instruments only would detect the change? (b) Which instrument measures mass directly? (c) How can a spring balance measure mass?



FIG. 6

9. An electric car is moving at the rate of 14 km. per hour. What is the rate in miles per hour?

10. A certain man weighs 160 pounds, and a certain boy weighs 30 kg. Express the difference in their weights in pounds.

11. (a) With a meter stick measure your height in meters. (b) Express the same in centimeters. (c) In giving your height, in each case state the *concrete unit* and the *numeric* used.

12. The Eiffel Tower in Paris is 300 m. high. What is the height of the tower in feet?

SECTION III

FORCE AND EQUILIBRIUM

9. **Force defined.** — No body at rest starts to move unless it is made to do so. Whenever we see a body begin to move, or a body in motion begin to stop or in any way to change its motion, whether it be in direction or in speed, we are sure that there is a *cause*. The cause is called *force*.

Force is any cause which tends to produce motion in a body at rest, or to produce change of motion in a body that is moving.

10. **Equilibrium of Forces.** — Force may act without causing a change of motion, as when two persons pull a chair equally in opposite directions; the chair does not move; nevertheless each pull “tends” to move it. In this case one force is said to *balance* the other. Every change of motion is caused by force; hence, any change in the motion of a body, whether it be in direction or in speed, is evidence that the body is acted upon by an *unbalanced* force. If a body be at rest, or if in motion its motion does not change, it is an indication that the forces acting on that body balance one another, or are *in equilibrium*. That the motion of a body remains unchanged is an indication, not that the body is free from the action of force, but that the forces acting on it are in equilibrium.

11. **Gravity.** — There is a variety of forces in nature, the most prominent of which is the force of *gravity*.

It is the force that causes unsupported bodies to fall to the earth. It is the force that gives weight to bodies when their fall is resisted. This force acting between the sun and the earth causes the latter to move in a curvilinear orbit around the former, instead of moving in a straight path and leaving the sun behind. No body in the universe is ever free from its action.

On a small scale, we have the force of *cohesion* which keeps the molecules of solids and liquids together and resists attempts to separate them. In gases there is no cohesion; on the contrary, the particles of gases ever tend to separate more and more widely.

12. Stress and Strain. — Force does not always cause a change in the motion of the body as a whole. It may cause simply a relative motion of its parts. In this latter case it causes a change in the size or shape of the body, as in the stretching of a rubber band, the bending of a strip of steel, the compression of air, and the flattening of a ball of soft putty. Change of size or shape by the application of force is called a *strain*.

In the cases just cited, and in all cases, strain is the result of a pair of balanced forces. A pair of balanced forces causing a strain is called a *stress*. If the pair of forces act away from each other, as in the act of stretching a rubber band, the stress is called a *pull*, or a *tensile stress*; if they act toward each other, as in the act of compressing air, the stress is called a *push*, or a *pressure*. A body lying on a table causes a strain (*i.e.*, a compression) in the matter of the table just beneath the body, and the elastic force (§ 13) of this strained or compressed

matter supports the body. The pair of opposing forces, *viz.*, the weight of the body acting downward and the elastic force acting upward, gives rise to a *pressure* between the body and the table.

13. Elasticity and Elastic Force. — A strained or stretched rubber band and a strip of steel that is bent tend to recover their original dimensions or shape. *Elasticity* is the property of a body by virtue of which it tends to recover from a strain. The molecular stress which tends to restore to a strained body its original form or volume is commonly called *elastic force*. Some substances, like putty, butter, and clay, are practically devoid of elasticity and are said to be inelastic.

Since a strained rubber band and a bent steel rod tend to recover their original form, they are said to possess *elasticity of form*. Since compressed air tends only to expand or increase in volume, it is said to possess *elasticity of volume*. Liquids and gases possess no elasticity of form.

As a summary of the above discussions, it may be stated that the effects of force on matter are twofold, — *change of motion and change of shape or size*.

14. Dynamometer. — Balanced forces may be measured by the strain which they produce, since *up to a certain limit strain is proportional to stress*. The common spring balance (Fig. 7) is used to measure a balanced force. It consists of a spiral spring of steel wire inclosed in a metal case. If weights proportional to the numbers 1, 2, 3, 4, etc., be hung upon the lower end of the spring, the pointer attached to the spring will move over

the scale, indicating elongations of the spring that are proportional to the several weights. If the ring of the

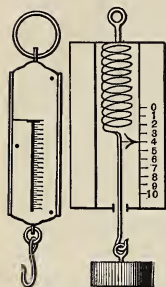


FIG. 7

spring balance be grasped by one hand and the hook by the other hand and the spring be elongated by a pull of the two hands, the pointer will indicate on the scale the measure of the pull. Any instrument used to measure force is called a *dynamometer*.

15. Gravitational Units of Force. —

For all engineering purposes and in the ordinary affairs of life a system of units is employed in which the unit of force is the force with which the earth attracts a given piece of matter (*e.g.*, the piece of platinum mentioned in § 7) at a certain fixed point on the earth's surface. The units (*e.g.*, kilogram, gram, pound, etc.) employed in such a system are called *gravitational units*. The unit of force in the metrical gravitational system is the force with which the earth attracts a mass of a kilogram when placed at the sea level in latitude 45°. In the British gravitational system the unit of force is the force with which the earth attracts a mass of a pound under similar conditions.

We learned (§ 7) that the attraction exerted by the earth on a given mass is not the same at all places; consequently the force with which the earth attracts (*i.e.*, the weight of) a kilogram-mass, for instance, is not everywhere a kilogram-force.

EXERCISES

1. (a) What causes change of motion? (b) What two changes of motion are possible?

2. If a spring balance be graduated in kilograms and a stone be hung from its hook and the pull of the stone (*i.e.*, the gravitation stress between the stone and the earth) be sufficient to draw the pointer down to the number 4 (Fig. 7), how great must be the muscular force applied to the ring to prevent the stone from moving?

3. (a) Which of the forces applied to the stone (muscular force or gravity) does the dynamometer measure in this case? (b) If the muscular force applied to the stone should be less than the force of gravity, what would happen to the stone? (c) If the muscular force should be the greater, what would happen to the stone?

4. (a) If a force of 8 kg. act on a body in an easterly direction and a force of 10 kg. act simultaneously on the same body in an exactly opposite direction, what will happen to the body? (b) How great is the unbalanced force that causes this result? (c) What is your conclusion respecting the effect of an unbalanced force acting on a body free to move? (d) What is your conclusion respecting the effect, as regards change of motion, of a pair of balanced forces acting on a free body?

5. How is pressure produced?

6. What is meant by the statement that liquids and gases possess no "elasticity of form"?

* 7. Define a kilogram-force; a gram-force.

8. What force causes a sled to slide downhill, and waters of rivers to flow seaward?

9. If a force acts on a body and does not move it, what do you infer?

CHAPTER II

FLUID PRESSURE

SECTION I

TRANSMISSIBILITY OF FLUID PRESSURE

16. **Difference in Respect to Transmission of Pressure between Fluids and Solids.** — If a glass globe and cylinder (Fig. 8) be filled with water, and a piston, *P*, be thrust into the cylinder, jets of water will be thrown not only from the aperture *A* toward which the force is applied and the piston moves, but equally from all the apertures.

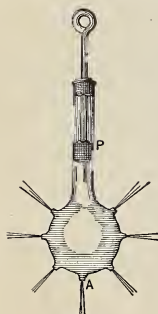


FIG. 8

If a cylinder of wood fit easily into a vessel (Fig. 9) and pressure as that of a weight be applied on the top, it causes a pressure through the wood to be exerted on the bottom of the vessel; but this is the only pressure exerted on the vessel.

This illustrates an important difference between the pressure of one solid on another, which is exerted only in the direction in which the force acts, and fluid pressure, which is transmitted in every direction.

When pressure is applied to a solid body, the body is incapable, on account of its rigidity, of transmitting the

pressure in other directions than that in which it is pressed. But fluids, on account of the mobility of their molecules, are incapable of resisting a change of shape when acted upon at any point by a force; and, hence, any force applied to a fluid body must be transmitted by the fluid in every direction.

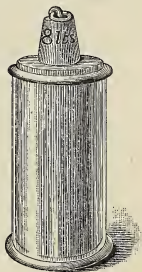


FIG. 9

17. Multiplication of Pressure; Pascal's Law.—Owing to the transmissibility of pressure any force impressed upon a body of fluid may be multiplied enormously. If, for example, we force the piston *A* (Fig. 10) into the tube *B* filled with a fluid (either liquid or gas), the plug *C* will be forced against the spring *D* with a force (disregarding friction) equal to the pressure

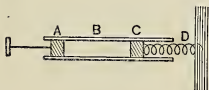


FIG. 10

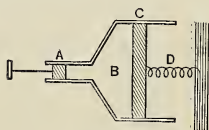


FIG. 11

upon *A*, if the area of *C* be equal to that of *A*. If *C* be larger than *A*, as in Fig. 11, the pressure per unit area of *C* remains equal to that per unit area of *A*; but as *C* is larger, the *total* pressure on *C* and on the spring *D* is greater in proportion to the larger area of *C*.

PASCAL'S LAW¹: A pressure applied to any portion of the surface of any fluid inclosed in a vessel is transmitted in all

¹ In physical science a *law* is a statement expressing the constant relation which exists between any phenomenon and its cause.

directions and is exerted undiminished upon every equal surface of the interior walls of the vessel. It follows that the total transmitted pressure on the interior of the vessel is equal to the area of the interior multiplied by the pressure per unit of area. In other words, pressure upon any interior surface is proportional to its area.

By the touch of a finger on a little piston a person can produce a pressure of a pound weight on every square inch of the interior surface of a vessel however large, if filled with a fluid, and the same amount on every square inch of every object immersed in it, even if that object consists of hundreds of square miles of sheets of tinfoil far enough apart for the fluid to penetrate between them.

Fluid pressure is expressed by stating the force exerted on a *unit area*, as 2 pounds per square inch, 5 g. per square centimeter, etc. It is always exerted in a direction at right angles to the surface pressed upon.

Experiment 1. — Fig. 12 represents a section of an apparatus called (from the number of uses to which it may be put) the

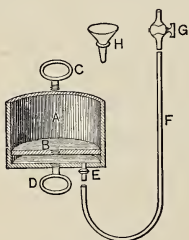


FIG. 12

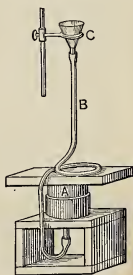


FIG. 13

seven-in-one apparatus. A is a hollow cylinder closed at one end. B is a tightly fitting piston which may be pushed into or drawn out of the cylinder by the detachable handle C when screwed

into the piston. *D* is another handle permanently connected with the closed end of the cylinder. *E* is a nipple, opening into the space below the piston. To this may be attached a thick-walled rubber tube, *F*. *G* is a stopcock, and *H* is a funnel, either of which may be inserted at will into the free end of the tube.

Support the seven-in-one apparatus with the open end upward, force the piston in, place on it a block of wood, *A* (Fig. 13), and on the block a heavy weight. Attach one end of the rubber tube *B* (12 feet long) to the apparatus and insert a funnel, *C*, in the other end of the tube. Raise this end as high as practicable and pour water into the tube. Explain how the few ounces of water standing in the tube can exert a pressure of many pounds on the piston and cause it to rise together with the burden that is on it.

We thus see that, paradoxical as it may seem, a small quantity of water may be made to support a very great weight.

Experiment 2.—Remove the water from the apparatus, place on the piston a 16-pound weight, and blow (Fig. 14) from the lungs into the apparatus. Notwithstanding that the actual pushing force exerted through the tube by the lungs probably does not exceed a few ounces, the slight increase of pressure caused thereby, when exerted upon the (about) 26 square inches of surface of the piston, causes it to rise together with its burden.

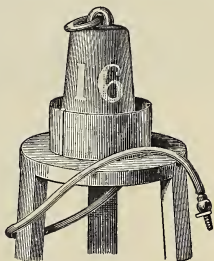


FIG. 14

18. The Hydraulic Press. —

Closely allied to the seven-in-one apparatus is the *hydraulic press*. Water drawn from a reservoir, *A* (Fig. 15), by a suction and force pump worked by a lever, *B*, is forced along the tube *C* into the cylinder *M*. This cylinder contains a plunger, *P*,

which works water-tight in the collar *F*. The plunger carries a plate, *G*, upon which are placed objects to be compressed. The water forced into the cylinder exerts upon the plunger a total upward pressure which is as many times greater than the downward pressure exerted upon the liquid through the plunger *H* as the area of

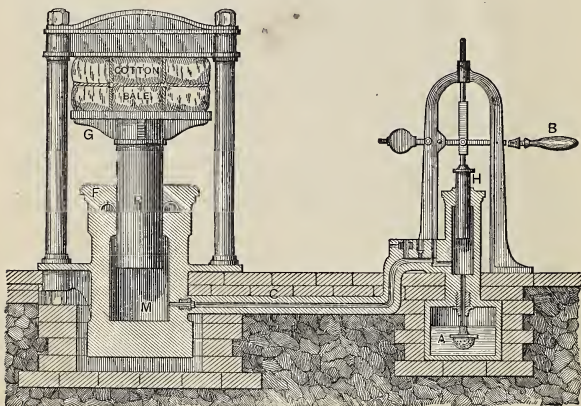


FIG. 15

the cross section of the plunger *P* is times greater than the area of the cross section of the plunger *H*. To obtain the entire theoretical gain of force that may be obtained by this machine, the ratio of the cross sections of the plungers is multiplied by the ratio of the two arms of the lever *B*. (See § 88.)

The pressure that may be exerted by these presses is enormous. The hand of a child can break a strong iron bar. But observe that, although the pressure exerted is very great, the upward

movement of the plunger P is very slow. In order that the plunger P may rise 1 cm., the plunger H must descend as many centimeters as the area of the cross section of P is times the area of the cross section of H . The disadvantage arising from slowness of operation is of little consequence, however, when we consider the great advantage accruing from the fact that one man can produce as great a pressure with the press as many men can without it. The modern engineer finds it a most efficient machine whenever great resistances are to be moved through short distances.¹

19. Pascal's Principle. — Fluids exert pressure due to their weight. Imagine a vessel filled with shot; the upper layer of shot will press upon the layer next beneath with a force equal to its weight, the second upon the third with a force equal to the sum of the weights of the first two, and so on. You conclude, therefore, that the pressure exerted upon the successive layers will be exactly *proportional to their depths*. In like manner, and for the same reason, *the pressure at different points in a liquid is proportional to the depth*.

Since shot possess a certain degree of mobility or freedom of motion around one another, their weight will cause, to some extent, a lateral pressure against one another and against the walls of the containing vessel. In consequence of the extreme mobility of the molecules of fluids, the downward pressure due to gravitation at any point in a fluid gives rise to an equal pressure at that point in all directions. Hence, the so-called *Pascal's principle*: *At any point in a fluid at rest the pressure is equal in all directions*.

¹ The so-called *hydraulic jack* acts on the same principle as the hydraulic press. In fact, the former is only a modification of the latter. The ratio of the diameters of the two plungers is made so great in some jacks that one man can lift a load of more than 100,000 pounds.

Thus, let a, b, c , etc. (Fig. 16), represent imaginary surfaces, and the arrowheads the direction of pressure exerted at points in these surfaces at equal depths in a liquid. The pressures exerted at these several points are equal.

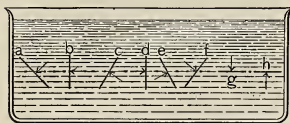


FIG. 16

The truth of this principle is obvious, for if there be any inequality of pressure at any

point, the unbalanced force will cause particles at that point to move, which is contrary to the supposition that the fluid is at rest. Conversely, *when there is motion in a body of fluid it is evidence of an inequality of pressures.*

If a glass tube (Fig. 17) be placed vertically in a stream of water with its lower end bent into a horizontal direction so as to face the stream, the water will rise in the tube to a height, say, AB . This height, technically called *head*, measures the inequality of pressures, or the unbalanced force which moves the water. Now the velocity of the stream is just that which would be produced by a head of water of the same magnitude. In other words, the velocity is proportional to the head; hence, this instrument may be used for determining the velocity of a stream of water.

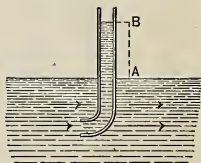


FIG. 17

Fig. 18 represents a jar of water having immersed in it several U-tubes with long and short arms. The shorter arms open in different directions, upward, downward, and sidewise. The bends of the tubes contain the same amount of mercury, and the openings of the short arms are all brought to the same level or depth in the water. The pressure of the water exerted downward, upward, and laterally forces the mercury to the same

hight in all the tubes, thus showing that *at the same depth pressure is equal in all directions*.

A (Fig. 19) is a glass jar containing water; *B* is a cylinder of wood thrust endwise into the water; *C* is a cylindrical glass vessel filled with water and thrust mouth downward into the jar of water, the water in this vessel being sustained by atmospheric pressure; and *D*

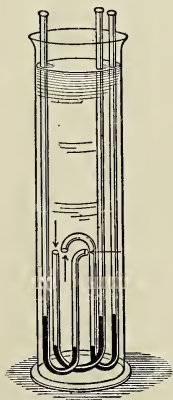


FIG. 18

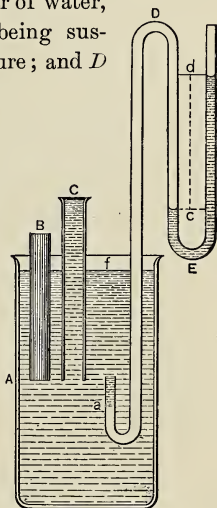


FIG. 19

is a glass tube bent as shown in the figure, containing water in the bend *E*. One end of this tube is thrust down into the jar of water, and the downward pressure of the water on the air in the tube is communicated to the water in the bend *E* and causes the water in the bend to rise higher in one arm than in the other. The

distance cd is equal to the depth of point a and measures the pressure of the water at point a . If the tube be raised so that a , the point where water and air are in contact, shall be at half the depth that it is at present, the distance cd between the two surfaces of the water in the bend will be reduced one half, showing that the pressure is half as great; in other words, that the *pressure is proportional to the depth*.

If, now, the tube be moved so that its end shall be under C , and at the same distance below the free surface (*i.e.*, the surface in contact with the atmosphere) of the water, the distance cd will be unchanged, although the height of the water above a , including the water in the vessel C , is now much greater. Move the end of the tube under the cylinder B so that the height of water immediately above shall be much less than at first; no change in pressure, as indicated by the height cd , will occur. From all this we conclude that *pressure at any point in a liquid, due to its weight, is directly proportional to the depth of the point below the free surface of the liquid*.

20. Pressure in Liquids is independent of the Shape of the Vessel and of the Quantity of Liquid. — This may be demonstrated with apparatus constructed from a large glass funnel and bent glass tubes, as shown in Fig. 20. If a small quantity of mercury be poured into vessels A and B so as to stand at the same height in the U-tubes of both, and then water be poured upon the mercury so as to stand at the same level, mn , in both A and B , it will be found that the mercury will be raised by the pressure of the superincumbent water to the same level,

cd, though the shapes of the vessels and the quantity of water which they contain are very different.

21. Methods of calculating Liquid Pressure. — Conceive a square prism of water (Fig. 21) in the midst of a body of water, its upper surface coinciding with the free surface of the liquid. Let the prism be 4 cm. deep and 1 cm. square at the end; then the area of one of its ends is 1 cm.², and the volume of the prism is 4 cc.

Now the weight of 4 cc. of water is 4 g.; hence, this prism must exert a downward pressure of 4 g. upon an area of 1 cm.² But at

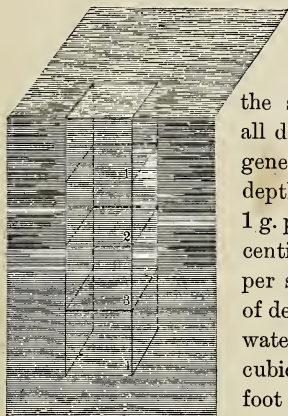


FIG. 21

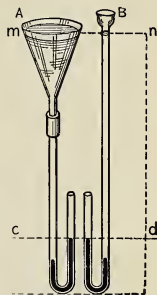


FIG. 20

the same depth the pressure in all directions is the same; hence, generally, the pressure at any depth in water may be taken as 1 g. per square centimeter for each centimeter of depth (≈ 1000 kg. per square meter for each meter of depth; or, since the weight of water is about 62.3 pounds per cubic foot, 62.3 pounds per square foot for each foot of depth). To determine the pressure at any given depth in any other liquid,

the water pressure at the given depth must be multiplied by the specific gravity (see Appendix) of the liquid.

22. Rules for calculating Liquid Pressure against the Bottom and Sides of a Containing Vessel. — The total pressure due to gravity on any portion of the horizontal bottom of a vessel containing a liquid is equal to the weight of a column of the same liquid whose base is the area of that portion of the bottom pressed upon, and whose height is the depth of the liquid in the vessel.

Evidently the lateral pressure at any point of the side of a vessel depends upon the depth of that point; and, as depth at different points of a side varies, to find the total pressure upon any portion of a side of a vessel, find the weight of a column of liquid whose base is the area of that portion of the side, and whose height is the average depth of that portion.

23. The Surface of a Liquid at Rest is Level. — By jolting a vessel the surface of a liquid in it may be made to assume the form seen in Fig. 22. Can it retain

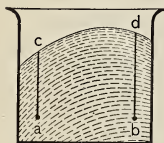


FIG. 22

this form? Take two particles of the liquid at the points a and b , on the same level. The total downward pressures upon a and b are in the ratio of their respective depths, ca and db . But since the pressure at a given depth is the same in all directions, ca and db represent the lateral pressures at the points a and b , respectively. But db is greater than ca ; hence, the particles a and b , and those lying in a straight line between them, are acted upon laterally by two unequal forces in opposite directions. Hence, the liquid cannot remain at rest in the position assumed; there will be a movement in the direction of the greater force, toward a , till there is equilibrium of forces, which will occur only

when the points *a* and *b* are equally distant from the surface; or, in other words, *there will be no rest till all points in the surface are on the same level.*

This fact is commonly expressed thus: "Water seeks its lowest level." In accordance with this principle, water flows down an inclined plane and will not remain heaped up. An illustration

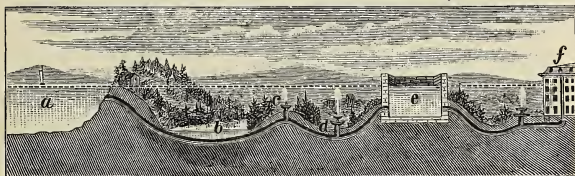


FIG. 23

of the application of this principle, on a large scale, is found in the method of supplying cities with water. Fig. 23 represents a modern aqueduct, through which water is conveyed from an elevated pond or river, *a*, beneath a river, *b*, over a hill, *c*, through a valley, *d*, to a reservoir, *e*, from which water is distributed by service pipes to the dwellings, *f*, in a city.

EXERCISES

1. The areas of the bottoms of vessels *A*, *B*, *C*, and *D* (Fig. 24) are equal. The vessels have the same depth and are filled with water. (a) Which vessel contains the most water? (b) On the bottom of which vessel is the pressure equal to the weight of the water which it contains?

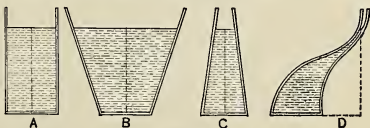


FIG. 24

(c) How does the pressure upon the bottoms of vessels *A*, *B*, *C*, and *D* compare, respectively, with the weight of the water in them?

2. Suppose that the area of the bottom of each vessel is 100 square inches, and the depth is 14 inches, what is the pressure on the bottom of each?

3. The bottom of vessel *A* is square. What is the total pressure against one of its vertical sides?

4. Let *A* (Fig. 25) be a closed cubical tank whose inside dimension is 10 cm. Leading from its side is a tube, *B*, whose top is 50 cm. above the interior top surface of the tank. (a) What mass of water will the tank (not including the tube) contain? (b) What will be the pressure on the entire bottom of the tank? (c) What on one of its sides? (d) Will there be any pressure on the top of the tank? Why? (e) Suppose the tank and tube to be filled with water, what pressure will be exerted upon the entire bottom of the tank? (f) What upon one of its sides? (g) What upon the top of the tank? (h) Suppose the liquid used were alcohol, how would answers to the above questions be ascertained?

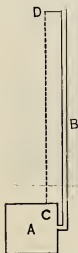


FIG. 25

5. Suppose that the area of the end of the large piston of a hydraulic press is 100 square inches, what must be the area of the end of the small piston that a force of 100 pounds applied to it may produce a pressure of 2 tons upon the large piston?

6. Take a glass U-tube (Fig. 26) about 40 inches high, having a stout rubber tube, *a*, attached, containing mercury with the surfaces at the same level in both arms. Blow into the tube; the surfaces of mercury will at once assume different levels. How will you determine the pressure which you exert through the air in the tube upon the mercury (the *specific gravity* of mercury being 13.59)?

7. (a) Suck air from *a*. What will happen to the mercury? (b) How may you determine the diminution of pressure which you produce by suction?

8. Take a similar tube containing water instead of mercury; connect it with a gas jet and turn on the gas. How would you determine how much greater (or less) its pressure is than that of the atmosphere?

9. How great is the pressure in fresh water at the depth of 50 feet?

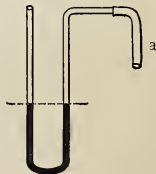


FIG. 26

10. (a) A house is supplied with water by a system of pipes from a distant reservoir, as is customary in cities. What data should you require in order to compute the pressure at any point in the pipe? (b) How much greater is the pressure at a point in the pipe in the cellar than at a point in the attic? (c) Is the pressure in the pipe the same when water is running from a faucet in the house as when the water is at rest?

11. Suppose that the aqueduct at point *b* (Fig. 23) is 150 feet below the level of the pond, what is the pressure at this point (expressed in tons per square foot) tending to burst the walls of the aqueduct?

12. What is the pressure in grams per square centimeter at a depth of 10 m. in fresh water?

13. The pressure at the bottom of a lake is four times the pressure at a depth of 2 m. What is the depth of the lake?

14. The diameter of the small plunger of a hydraulic press is 10 cm.; that of the large plunger is 1 m.; the pressure applied to the small plunger is 200 kg. What load is sustained on the large plunger?

SECTION II

ATMOSPHERIC PRESSURE

24. **Introduction.**—Scarcely seven generations have passed since people fully grasped the idea that we live and move at the bottom of an ocean of atmospheric air which forms its outermost layer and extends above our heads many miles, the weight of which presses upon us and upon all objects within our reach with a force of about one ton on every square foot of surface.¹

We live without inconvenience at the bottom of such a heavy atmospheric ocean, just as deep-sea fish do at the bottom of the sea. The external pressure, about 15 pounds per square inch,

¹ A liter of dry air at sea level at the temperature of melting ice weighs about 1.293 g. The pupil should compute the approximate weight of the air which his schoolroom contains.

is balanced by the internal pressure of the gases contained in the pores of the flesh and liquids of our bodies. If we enter a highly rarefied air, the gases within our bodies expand, sometimes bursting blood vessels. Bleeding from the nose or lungs is a familiar occurrence at high altitudes where the air is very rare.

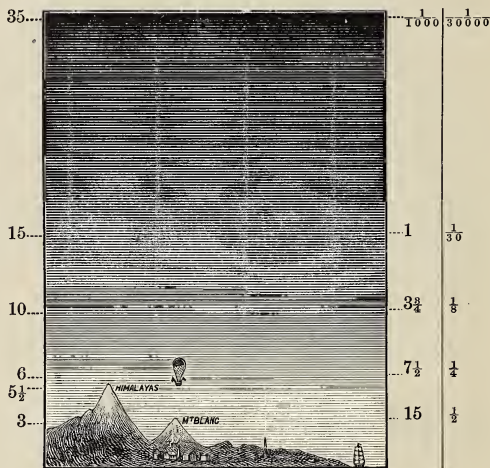


FIG. 27

Evidently the pressure in the atmosphere due to its weight increases with the depth, or — since in our position we are more accustomed to speak of *height* in the atmosphere — decreases with the height. The pressure does not diminish regularly with the height as in the liquid ocean; but at any given point it is equal in all directions. Air is very compressible; the lower strata of the atmosphere, which sustain the weight of the

upper strata, are much compressed and are therefore much denser than the upper strata. The density of the air diminishes more rapidly than the height above sea level increases. Owing to this fact more than half of the atmospheric matter is within 4 miles of the sea level, notwithstanding that the atmosphere extends, it is thought, 200 miles above the earth.¹



FIG. 28

Experiment 1. — Fill, or partly fill, a tumbler with water, cover the top closely with a card or writing paper, hold the paper in place with the palm of the hand, and quickly invert the tumbler (Fig. 28). How is the water supported?

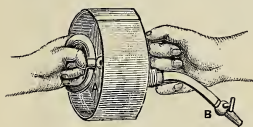


FIG. 29

Experiment 2. — Force the piston *A* (Fig. 29) of the seven-in-one apparatus quite to the closed end of the hollow cylinder, and close the stopcock *B*. Try to pull the piston out again. Why do you not succeed? Hold the apparatus in various positions, so that the atmosphere may press down, laterally, and up, against the piston.

You discover no difference in the pressure which it receives from different directions.

¹ The shading in Fig. 27 is intended to indicate roughly the variation in the density of the air at different elevations above sea level. The figures in the left margin show the height in miles; those in the first column on the right, the corresponding average height of the mercurial column in inches; and those in the extreme right, the density of the air compared with its density at sea level. If the aerial ocean were of a uniform density equal to that at sea level, its height would be less than 5 miles. The highest peaks of the Himalaya Mountains would rise above it.

25. How Atmospheric Pressure is measured.

Experiment 3. — Take a U-shaped glass tube (Fig. 30), half fill it with water, close one end with a thumb, and tilt the tube so that the water will run into the closed arm and fill it; then restore it to its original vertical position. Why does not the water settle to the same level in both arms?

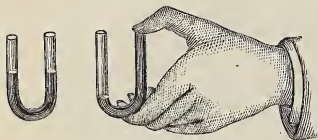


FIG. 30

Let Fig. 31 represent a U-shaped glass tube about 34 inches in height,

closed at one end and having a bore of 1 square-inch section. The closed arm having been filled with mercury, the tube is placed with its open end upward, as in the cut. The mercury in the closed arm sinks about 2 inches to *A* and rises 2 inches in the open arm to *C*, leaving the surface *A* 30 inches higher than the surface *C*. This can be accounted for only by the atmospheric pressure on the surface of mercury at *C*. The column of mercury *BA*, containing 30 cubic inches, is an exact counterpoise for a column of air of the same diameter extending from *C* to the upper limit of the atmospheric ocean.

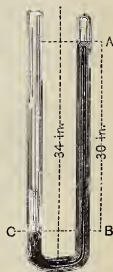


FIG. 31

The weight of the 30 cubic inches of mercury in the column *BA* is 14.7 pounds. Hence, the weight of a column of air of 1 square-inch section, extending from the surface of the sea to the upper limit of the atmosphere, is about 14.7 pounds. But in fluids gravitation causes equal pressure in all directions. Hence, *at the*

level of the sea all bodies are pressed upon in all directions by the atmosphere by a force of about 14.7 pounds per square inch, or about 1 ton per square foot.

26. Standard Pressure.—Many physical operations require a standard pressure for reference. The standard generally adopted is the pressure, per square centimeter, equal to the weight of a column of mercury 76 cm. in height resting on each square centimeter; that is, it is equal, on each square centimeter, to the weight of 76 cm.³ of mercury.¹ This is equal to the weight of about 1033 g. of water. Physicists generally express fluid pressure in terms of the millimeters (or centimeters) of mercury at 0° C. that the given pressure would sustain in a vacuum tube. Thus, for example, the average sea-level atmospheric pressure is expressed as 76 cm., or 760 mm.

27. The Barometer.—The height of the column of mercury supported by atmospheric pressure is proportional to the pressure *per unit area* and is quite independent of the total area of the surface of the mercury pressed upon; hence, the apparatus is more conveniently constructed in the form represented in Fig. 32.

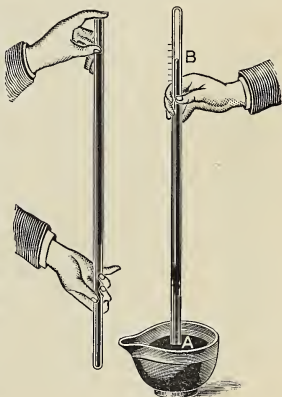


FIG. 32

¹ A unit of pressure of 15 pounds per square inch is quite generally adopted by engineers in expressing very large pressures, and is called an *atmosphere*.

A straight tube about 34 inches long is closed at one end and filled with mercury. The tube is inverted, with its open end tightly covered with a finger, and this end is inserted into a vessel of mercury. When the finger is withdrawn the mercury sinks until there is equilibrium between the downward pressure of the mercurial column *AB* and the pressure of the atmosphere.

The empty space at the top of the tube is called a *Torricellian*¹ vacuum.



FIG. 33

An apparatus designed to measure atmospheric pressure is called a *barometer* (pressure measurer). A common and inexpensive form of barometer is represented in Fig. 33. To protect the mercury from falling dust, the cistern is inclosed in a small closet, *A*, which is not, however, air-tight. Beside the tube, and near its top, is a scale, graduated in inches or centimeters, indicating the height of the mercurial column. For ordinary purposes this scale needs to have a range of only three or four inches, so as to include the maximum fluctuations of the column.

Such a barometer is subject to a small error in its reading, which is eliminated in the more expensive kinds. In refined scientific work it is necessary to make suitable allowances for expansion and contraction of the mercury and the scale attending changes of temperature.

Fluctuations in barometric pressure are of frequent occurrence. Some of the many conditions which

¹ The first barometer was constructed by Torricelli, a Florentine, in 1643.

influence atmospheric pressure are *changes in temperature, humidity of the air, and currents in the atmospheric ocean.*¹

28. Barometric Measurement of Hights.—Since atmospheric pressure varies with the hight above sea level, it is evident that changes in elevation may be determined from changes of pressure as indicated by the barometer. For example, the hight of a mountain may be ascertained from barometric readings made at the same time on the summit and at sea level. For moderate hights the barometric column falls at a nearly uniform rate of 1 inch for every 900 feet of ascent.

EXERCISES

1. The average barometric pressure in the city of Denver is 612 mm. What is the corresponding pressure in grams per square centimeter?

2. The pressure of the atmosphere on the earth's surface is practically equal to the pressure of an ocean of fresh water covering the earth to what depth? *3413.54 = 3317 ft*

3. What is the hight of the barometric column when the pressure of the air is 1045 g. per square centimeter?

4. If the mercury in the barometer falls 15 mm., how great is the change in atmospheric pressure expressed in grams per square centimeter? *1012.0*

5. When the barometer stands at 760 mm. what is the pressure in kilograms per square decimeter?

¹ The barometer is sometimes called a *weather glass*, chiefly because its scale frequently bears the words *fair, rainy, storm*, etc. These words are very objectionable, since they are totally misleading from a meteorological point of view. To form a forecast of the weather of much value, a barometer, a thermometer, and a hygrometer must be consulted, and one must be familiar with the laws which govern the relations between atmospheric pressure, temperature, moisture, etc.

6. The top of Mt. Blanc, in Switzerland, is $3\frac{1}{2}$ miles above sea level. The average atmospheric pressure on the summit of this mountain is 38 cm. Only what portion of the matter of the atmospheric ocean is above the summit? (See Fig. 27.)

7. Examine Fig. 27 and determine about what portion of the mass of the atmosphere is within 15 miles of the earth's surface.

8. Is it essential that the barometer tube be of uniform bore?

9. Explain what is meant by (a) a "head" of 10 feet of water; (b) a pressure of 20 inches of mercury.

10. Compute the pressure due to a head of water of 10.47 m. (34 feet) in kilograms per square decimeter.

SECTION III

RELATION BETWEEN THE DENSITY, THE VOLUME, AND THE PRESSURE OF A BODY OF GAS

29. **Pressure of Confined Gases due to Molecular Motion.** — When a quantity of gas is confined in a close vessel it exerts a pressure on all parts of the interior of the vessel. This pressure is out of all proportion to the weight of the gas, and in fact is not due to its weight. The pressure may exceed the weight a million times. The pressure cannot be due to anything similar to the reaction of a compressed spring, for the molecules of a gas are free from one another's influence. It can be accounted for only as the *sum of the impacts of the separate molecules which continuously bombard the sides of the vessel*. When the volume of a body of gas is reduced by compression the pressure which it exerts per unit area is increased, because more molecules now strike a unit area in a unit of time.

30. **Elasticity of Gases.** — *The elasticity of gases is perfect.* By this is meant that the force exerted in

expansion is equal to the force used in compression, and that, however much a fluid is compressed, it will always completely regain its former volume when the pressure is removed. Hence, the barometer, which measures the compressing force of the atmosphere, also measures at the same time the elastic force of the air. A so-called *vacuum gauge* (Fig. 34) is simply a short mercury barometer, — short because it is seldom required to make measurements except in tolerably high vacua, where the mercurial column is correspondingly low.

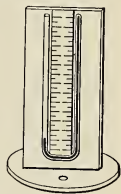


FIG. 34

This apparatus, placed under the receiver of an air pump from which air is exhausted, will measure the elastic force or pressure of the air in the receiver. This known, the degree of exhaustion is readily determined.

Thus, for example, suppose that a barometer outside the receiver stands at 755 mm., and after exhaustion the vacuum gauge inside the receiver stands at 10 mm.; then the pressure has been diminished ($755 - 10 =$) 745 mm. This indicates that $\frac{745}{755}$ of the air has been removed.

31. Boyle's (or Mariotte's) Law.

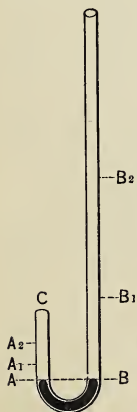


FIG. 35

Experiment. — Take a bent glass tube (Fig. 35), the short arm being closed, and the long arm, which should be at least 85 cm. long, being open at the top. Pour mercury into the tube till the surfaces in the two arms are at the same level, AB .

The body of air to be experimented with is in the short arm between A and C . The dimensions of this body can vary only in height; hence, its height, H , may represent its volume.

Measure H (*i.e.*, the distance between A and C) and regard the number of centimeters as representing the volume, V . Its pressure, P , evidently is the same as that of the atmosphere at the time. Consult a barometer and ascertain the height of the barometric column; represent this height by P . Pour a little mercury into the tube; the mercury rises, say, to A_1 and B_1 . Measure the vertical distance between A_1 and C ; this number represents the volume V_1 of the body of air now. Measure the vertical distance between A_1 and B_1 ; this number represents the increase in pressure, which, added to P , gives its present pressure, P_1 .

Now pour more mercury into the tube, so that it will rise to, say, A_2 and B_2 . Determine as before the new volume V_2 and the new pressure P_2 . So continue to add mercury a third and a fourth time, and get new values for the volume V_3 and V_4 and for the pressure P_3 and P_4 . Arrange the results as follows:

$V = \dots$	$P = \dots$	$V \times P = \dots$
$V_1 = \dots$	$P_1 = \dots$	$V_1 \times P_1 = \dots$
$V_2 = \dots$	$P_2 = \dots$	$V_2 \times P_2 = \dots$
etc.	etc.	

It will be found that the series of products in the last column are approximately equal (due allowance being made for errors in measurement, etc.); consequently, the product of the volume of a body of gas multiplied by its pressure is constant, and the volume varies inversely as its pressure. Hence the (Boyle's) law:

The volume of a body of gas at a constant temperature varies inversely as its pressure, density, and elastic force.

EXERCISES

1. If the volume of a certain body of gas be 500 cc. when its pressure is 800 g. per square centimeter, what is the volume of the same body when its pressure is 1200 g. per square centimeter?
2. If a body of air whose volume is 1 m.³ and whose pressure is 760 mm. expands and occupies 4.5 m.³, what will be its pressure?
3. A bubble of air liberated at a depth of 2 m. in water has a volume of 3 cm.³. What will be its volume when it has risen 1 m.?

4. Air is rarefied in the receiver of an air pump so that the difference in level of the two surfaces of mercury in the vacuum gauge is 2 mm. What is the elastic force of the remaining air, expressed in grams per square centimeter?

5. A mass of air occupies 80 cc. when the pressure is 100 mm. What space will it occupy when the pressure is 150 mm.?

6. A mass of air occupies 160 cc. when the pressure is 760 mm. What must be the pressure that it shall occupy only 50cc.?

7. Suppose that, on a day when the pressure of the air is 756 mm., air is exhausted from the receiver of an air pump until the mercury in the barometer *F* (Fig. 36) stands at 30 mm., what per cent of the air has been removed?

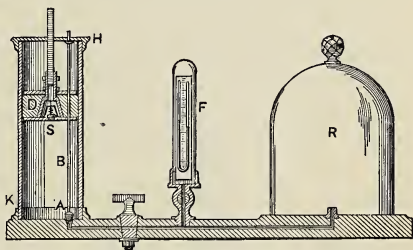


FIG. 36

SECTION IV

PUMPS AND SIPHONS

32. The Air Pump.—The air pump is used to rarefy air in a closed vessel. Fig. 36 will illustrate its operation. *R* is a glass vessel, called a *receiver*, within which the air is to be rarefied; *HK* is a hollow cylinder of brass, called the *pump barrel*; *D* is an accurately fitting *piston*, in which is an *outlet valve*, *S*, opening upward when the pressure below is greater than that above. An *inlet valve*, *A*, at the bottom of the barrel is carried by a rod, *B*, that passes through the piston and slides through it with some friction. *F* is a glass vessel communicating with *R*, containing a barometer, or pressure gauge, to indicate the degree of exhaustion.

A downstroke of the piston carries down the rod *B* and closes the valve *A*, while the elastic force of the air below *D* opens *S*,

and the confined air passes to the upper side of the piston. The succeeding upstroke of the piston closes *S*, lifts *B*, and opens *A*. The upward motion of *B* is limited by a shoulder which it carries near its upper end. The air that passes through *S* is forced out through an opening (closed by a valve) at the top of the barrel, and the air in *R* expands and fills again the barrel below *D*. Thus, at each double stroke a certain fraction of the air remaining in *R* is removed; but, on account of leakage and other imperfections, the pressure of the air left in *R* can be reduced by the best pumps but a little below 1 mm. of mercury. When a higher degree of exhaustion is required use is made of mercury pumps. (See § 142 of the author's *Principles of Physics*.)

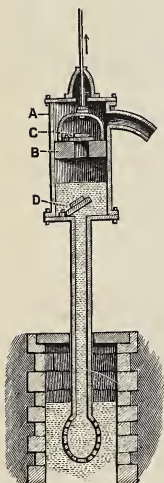


FIG. 37

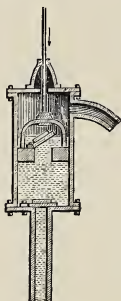


FIG. 38

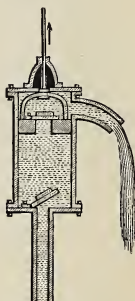


FIG. 39

It is obvious that if *S* and *A* open downward instead of upward, then, as the piston is raised and depressed, air is compressed in *R*. A *condenser* is merely a pump with its valves reversed, and is used to condense air.

33. Lifting Pump for Liquids. — The common *lifting pump* is constructed like the barrel of an air pump. Fig. 37 represents the piston *B* in the act of rising. As the air is rarefied below it, water rises in consequence of atmospheric

pressure¹ on the water in the well and opens the lower valve *D*. Atmospheric pressure closes the upper valve *C* in the piston. When the piston is pressed down (Fig. 38) the lower valve closes, the upper valve opens, and the water between the bottom of the barrel and the piston passes through the upper valve above the piston. When the piston is raised again (Fig. 39) the water above the piston is raised and discharged from the spout.

34. Force Pump. — In this pump the ordinary piston with valve is replaced by a solid cylinder of metal, *B* (Fig. 40), called the *plunger*. This passes through a stuffing box, *D*, in which it fits airtight. Valves opening upward and outward are placed at *A* and *C*, respectively. When the plunger is raised *A* opens and *C* closes, and water is raised into the barrel by atmospheric pressure. When the plunger descends *A* closes and *C* opens, and the water is forced up through the pipe *E*. An air dome, *F*, is usually connected with these pumps to regulate the pressure so as to give through the delivery pipe a very steady stream. This dome contains air. When the plunger descends it forces water into the dome and compresses the air within. As soon as the downstroke of the piston ceases the valve *C* closes, and the compressed air in the dome forces the water out through *E* in a continuous stream.

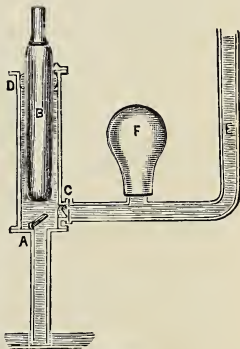


FIG. 40

35. Siphon. — Take two vessels, *A* and *B* (Fig. 41), containing water (or other liquid). Let the surface of the liquid in one vessel be lower than the surface in the

¹ The statement that "Nature abhors a vacuum" was used ages ago to account for various phenomena, — among them the rise of water in pumps.

other. Bend a tube, CC' , of any kind (*e.g.*, rubber or glass) into the form of the letter U, fill it with some of

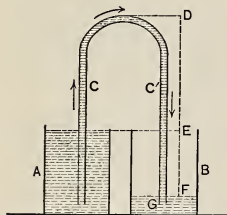


FIG. 41

the same liquid, cover the ends with your fingers, invert the tube, dip the ends of the tube into the liquids and remove the fingers. Liquid will flow from the vessel in which the liquid has a higher level into the other vessel. The pressure of the atmosphere, per square centimeter, on the free surfaces of the liquids in the

two vessels is nearly the same, but the downward pressure of liquid in the arm C' is greater than the pressure of liquid in the arm C by the pressure of the column of liquid EF . The pressure of the column of liquid EF represents very nearly the unbalanced force which causes the liquid to flow from vessel A to vessel B . When will the liquid cease to flow? A tube used in this manner for transferring a liquid, through the agency of atmospheric pressure, is called a *siphon*.

SECTION V

BUOYANT FORCE OF FLUIDS

36. The Principle of Archimedes. — We all know that it is easier to raise a stone in the water than in the air. If you hang a stone or a brick from a spring balance and weigh it first in the air and then in the water, you find that its weight in the water is considerably less than in

the air. What is the cause of this apparent loss of weight in liquids?

Suppose $dcba$ (Fig. 42) to be a cubical block of marble immersed in a liquid. The pressure of the liquid against its opposite sides is in equilibrium, and there is no sensible effect of this pressure; but, inasmuch as pressure is proportional to depth, the upward pressure on the bottom of the block must be greater than the downward pressure on the top in proportion as the bottom is deeper than the top. This unbalanced force is commonly called a *buoyant force*, and *a body immersed in a fluid is buoyed up in consequence of the unequal pressures upon its top and bottom at their different depths*. How great is this apparent loss of weight, or buoyant force?

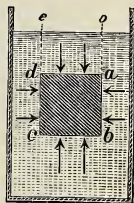


FIG. 42

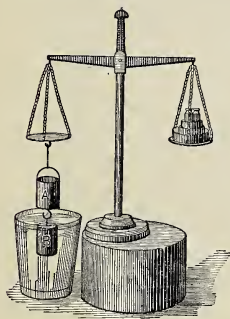


FIG. 43

Experiment 1. — Suspend from one arm of a balance beam a cylindrical bucket, A (Fig. 43), and from the bucket a solid cylinder, B , whose volume is exactly equal to the capacity of the bucket; in other words, the cylinder will just fill the bucket. Counterpoise the bucket and cylinder with weights.

Place beneath the cylinder a tumbler of water and raise the tumbler until the cylinder is completely submerged. The buoyant force of the water destroys the equilibrium. Pour water into the bucket. When it becomes just even full the equilibrium is restored.

Now it is evident that the cylinder immersed in the water displaces its own volume of water, or just as much water as fills the bucket; but the bucket full of water is just sufficient to restore the weight lost by the submersion of the cylinder.

The principle we are discussing is just as true of gases as of liquids (see § 38); hence, a body immersed in a fluid loses exactly as much of its weight as is equal to the weight of the fluid it displaces. This important truth was discovered by the noted mathematician and philosopher Archimedes, about 240 B.C., and is known as the *Principle of Archimedes*.¹

37. Floating Bodies.—Bodies like cork floating on liquids apparently lose all their weight, *i.e.*, they sink until they reach a depth where the upward pressure is just equal to their weight and the body is in equilibrium. The weight of the liquid displaced by a floating body is equal to the weight of the body.

This statement may be verified as follows: Take a vessel like that shown in Fig. 44 and fill it with water until the water is just ready to flow from the tube *A*. Take a block of wood that will float in water, weigh it, and also weigh vessel *B*. Then carefully place the block in the water, catching the overflow in *B*. Find

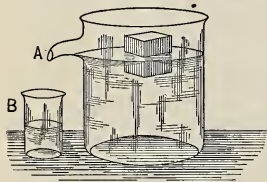
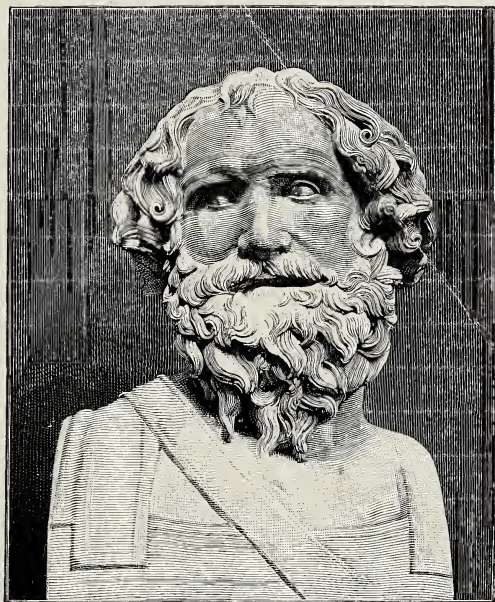


FIG. 44

¹ Previously the descent of heavy bodies and the rising of light bodies in liquids were explained on the assumption that "every object seeks its place. The place of heavy bodies is below; the place of light bodies is above."



ARCHIMEDES (287-212 B.C.)

Greatest mathematician of his age ; skilled in various branches of natural philosophy; discoverer of the Law of Buoyancy of Fluids. Bust in National Museum, Naples.

the weight of the water displaced, which will be found to be equal to the weight of the block.

38. The Principle of Archimedes applied to Gases. — The difference between the downward pressure on the top and the upward pressure on the bottom of bodies in the air is a vertical upward force equal to the weight of the displaced air. Consequently bodies weigh more in a vacuum than in the air, and we get the *absolute weight* of a body only when the weighing is done in a vacuum. For example, a body whose volume is 1 dm.³ weighs about 1.29 g. more in a vacuum than in the air.

Experiment 2. — Place a baroscope (Fig. 45), consisting of a scale beam, a small weight, and a hollow brass sphere, under the receiver of an air pump and exhaust the air. In the air the weight and sphere balance each other; but when the air is removed the sphere sinks, showing that in reality it is heavier than the weight. In the air each is buoyed up by the weight of the air it displaces; but as the sphere displaces more air, it is buoyed up more. Consequently, when the buoyant force is withdrawn from both, their equilibrium is destroyed.

The density of the atmosphere is greatest at the surface of the earth. A body free to move cannot displace more than its own weight of a fluid; therefore a balloon, which is a large bag filled with a gas many times lighter than air at the sea level, will rise till the weight of the balloon,¹ together with its car and cargo, equals the weight of the air displaced.

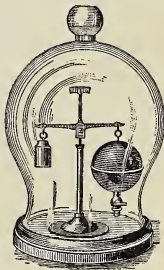


FIG. 45

¹ In 1862 two men in England ascended in a balloon until the barometer recorded 9.75 inches, corresponding to 29,000 feet (about 5½ miles), when both became unconscious.

EXERCISES

1. On what condition will a body rise in air ?
2. (a) Compare the absolute weights of a pound of feathers and a pound of lead. (b) Compare the weights of the same in the air. *Lead*
3. The capacity of a certain balloon when inflated is 4000 m.³. When not inflated it weighs 80 kg. A liter of air at sea level weighs about 1.29 g. and a liter of hydrogen gas under the same pressure weighs 0.09 g. If the balloon be inflated with hydrogen gas, how great a weight will it support? *Ans. 4720 kg.*

SECTION VI

DENSITY AND SPECIFIC GRAVITY

39. Terms defined ; Formulas. — The density of a substance is defined as the mass of one unit of volume of that substance, usually expressed in grams per cubic centimeter. We infer from this definition that

$$(1) \text{ density} = \frac{\text{mass}}{\text{volume}}; \text{ hence,}$$

$$(2) \text{ mass} = \text{density} \times \text{volume, and}$$

$$(3) \text{ volume} = \frac{\text{mass}}{\text{density}}.$$

The specific gravity of a substance is the ratio of the weight of a body of that substance to the weight of an equal volume of some standard substance. The standard adopted for solids and liquids is distilled water at some definite temperature. Hence, for solids and liquids,

$$(4) \text{ specific gravity} = \frac{\text{weight of the body}}{\text{weight of an equal volume of water}}.$$

According to Archimedes' Principle,

loss of weight in water = weight of an equal volume of water ;

hence,

$$(5) \text{ specific gravity} = \frac{w}{w - w'},$$

in which w = weight of the body, w' = the weight of the body in water, and $w - w'$ = the loss of weight in water, *i.e.*, the weight of an equal volume of water.

It will be seen that when the gram and the cubic centimeter are used as units in expressing density the numbers which express the density and the specific gravity of any substance are numerically equal. For example, the density of lead is 11.3 g. per cubic centimeter and the specific gravity of lead is 11.3 (an abstract number).

40. Methods of finding the Specific Gravity of Bodies.

(1) *Solids.*

Experiment 1. — From a hook beneath a scale pan (Fig. 46) suspend by a fine thread a small body of the substance whose specific gravity is to be found and weigh it, while dry, in the air. Then immerse the body in a tumbler of water (see that it is covered with water and nowhere touches the tumbler) and weigh it in water. The difference between its weight in air and its weight in water ($w - w_1$) is the weight of an equal volume of water. Apply formula (5), § 39.

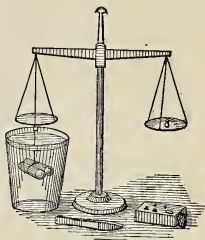


FIG. 46

Experiment 2. — Take a piece of cork or a small block of pine or other kind of wood ; also a strip of sheet lead whose weight is at least half that of the block and whose length is sufficient for it to be wound once around the block. Weigh the

dry block; also the dry lead. Suspend the lead sinker and weigh it in water. Fold the lead sinker around the block and weigh both when immersed in water. Subtract their combined weight in water from the sum of their weights in air; this gives the weight of water displaced by both. Subtract from this the weight lost by the lead alone, and the remainder is the weight of water displaced by the cork. Apply formula (4).

(2) Liquids.

Experiment 3. — Take a so-called *specific-gravity bottle*, i.e., a bottle made so as to hold, when the stopple is pressed in, an exact (round) number of grams of water, e.g., 100 g. or 1000 g. Fill the bottle with the liquid whose specific gravity is sought. Place it on a scale pan (Fig. 47), and on the other pan place a piece of metal, *a*, which is an exact counterpoise for the bottle when empty. On the same pan place other weights, *b*, until there is equilibrium, and thus weigh the liquid contents of the bottle. The water capacity of these bottles is usually etched on the bottles. The weight of the liquid in the bottle divided by the water capacity of the bottle will give the specific gravity of the given liquid.

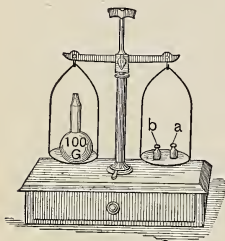


FIG. 47

Experiment 4. — Weigh a pebble in air, also in water, and find the weight of water displaced by it. Wipe the stone, weigh it in some other liquid whose specific gravity is sought, and find the weight of this liquid displaced by the stone. You now have the weights of equal volumes of the two liquids. Compute the specific gravity of the latter liquid by formula (4).

41. The Hydrometer. — One form of this instrument consists of a closed glass tube, *A* (Fig. 48), terminating in a bulb loaded with shot or mercury to keep it upright

when placed in a liquid. It is merely placed in the liquid to be tested, and the specific gravity is read from a graduated scale on the stem at that point which is at the surface of the liquid. The less the density of the liquid, the deeper the instrument sinks. Hydrometers are much used for testing the purity of milk, alcohol, etc., and are then graduated with special reference to the liquids for which they are to be used, and hence take the special names of lactometers, alcoholometers, etc.

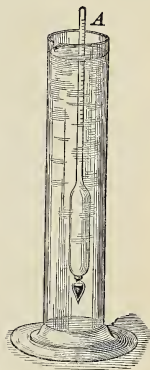


FIG. 48

EXERCISES

(In the solution of the following exercises frequent reference must be made to the Tables of Specific Gravity in the Appendix.)

1. (a) Why does a body immersed in a fluid lose weight? (b) How much weight does it lose?

2. A body floating on a liquid displaces how much liquid?

3. (a) Why does a balloon rise? (b) When will a balloon cease to rise?

4. Under what conditions will a body sink in a liquid?

5. (a) What is meant by the statement that the specific gravity of gold is 19.3? (b) What is the density of gold?

6. Will ice sink or float in water? Why?

7. What is the density of alcohol?

8. At what temperature has water a density of 1 kg. per cubic decimeter?

9. (a) What is meant by the statement that the specific gravity of benzine is 0.87? (b) What is the density of benzine? (c) What would a liter of benzine weigh? (d) Would benzine rise or sink in water?

10. A block of wood floating on water displaces 10 kg. of water. What is the weight of the block?

11. In which liquid, water or alcohol, would a block of pine wood sink farther?

12. The area of the cross section of a wooden prism is 4 cm^2 . Placed vertically in water it sinks 15 cm. What is the weight of the prism?

13. Fig. 49 represents a beaker graduated in cubic centimeters. Suppose that when water stands in the graduate at 50 cc. a pebble is dropped into the water and the water rises to 75 cc. (a) What is the volume of the stone? (b) How much less does the stone weigh in water than in air? (c) What is the weight of an equal volume of water?

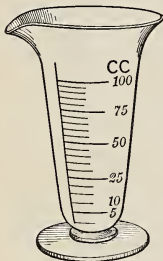


FIG. 49

14. If a piece of cork is floated on water in a graduate and displaces (*i.e.*, causes the water to rise) 10 cc., what is the weight of the cork?

15. You wish to measure out 60 g. of alcohol. To what number on a beaker graduated in cubic centimeters will you pour the alcohol?

16. State how you would measure out 50 g. of nitric acid.

17. A measuring beaker contains 40 cc. of mercury. What does the mercury weigh?

18. What is the volume of 40 g. of gold? of 40 g. of aluminum?

19. A sponge thrown on water floats at first, but after a time sinks. Is the specific gravity of the fibers of sponge greater or less than that of water?

20. Why will a tin basin or iron steamship float on water?

21. Find the weight of a cube of aluminum of 1 dm. edge.

22. A body weighs 1200 g. in air and 950 g. in water. What is its density?

23. A piece of metal weighing in air 70.4 g. is placed in a tumbler filled with water. The overflowing water is found to weigh 8.3 g. What is the specific gravity of the metal?

24. If 720 g. of silver be suspended in water, what will be the tension of the supporting string?

25. What is the specific gravity of a substance whose density is 80 pounds per cubic foot?

26. (a) What is the density, expressed in pounds per cubic foot, of a body whose specific gravity is 2.5? (b) What is the density of the same body expressed in grams per cubic centimeter?

27. A piece of zinc weighs in air 170.4 g., in water 146.4 g. What is the specific gravity of zinc?

28. What is the volume of 25 g. of zinc?

29. What is the weight of 40 cc. of zinc?

30. What support will water give to 75 g. of zinc immersed in it?

31. How much will 100 g. of zinc weigh in water?

32. How much will 100 g. of zinc weigh in sea water?

33. A piece of zinc weighs 42 g. in water. How much does it weigh in air?

34. Find the weight of a liter of olive oil.

35. Find the volume of 50 g. of olive oil.

36. A piece of lead and a piece of wood balance each other when weighed in air. Which body has the greater mass?

37. A body floats with one third its volume under water. What is its specific gravity?

38. (a) Two bodies, *a* and *b*, of different volumes, weigh the same in water. Which will weigh the more in sea water? (b) Which will weigh the more in air?

39. What will be the weight of 100 cc. of cast iron in water?

40. A rectangular body of cork 12 cm. long, 10 cm. wide, and 8 cm. thick weighs 230.4 g. (a) What is the density of cork? (b) What would a cubic decimeter of cork weigh?

41. Find the volume of 500 g. of lead.

42. Find the weight of 1 l. of water at 20° C.

43. (a) Find the buoyant force on 1 dm.³ of cast iron when immersed in water; (b) when immersed in glycerine.

44. Find the buoyant force on 1 kg. of cast iron when immersed in water.

45. A piece of glass weighs in air 40 g., in water 24 g., and in milk 23.4 g. (a) What is the specific gravity of the glass? (b) What is the specific gravity of the milk?

46. A block of wood weighs in air 150 g. A lead sinker weighs 35 g. in water. Both weigh 24 g. in water. (a) How great is the buoyant effect of the water upon the block? (b) What is the specific gravity of the wood?

47. A solid whose specific gravity is 0.5 and whose weight in air is 80 g. is fastened to a sinker that weighs 120 g. alone in water. How much will both together weigh in water?

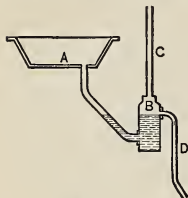


FIG. 50

48. A piece of cork weighs in air 240 g. It is fastened by a thread to the bottom of a vessel so as to keep it entirely immersed. Find the tension of the thread.

49. How could you find the volume of an irregularly shaped stone?

50. How could you find the capacity of an irregularly shaped cavity in a body?

51. *A* (Fig. 50) represents a sink, *B* a trap, *C* a pipe leading to open air outside the house, and *D* a pipe leading to a cesspool or sewer.

(a) Explain how water may flow from the sink to the sewer but sewage gases be prevented from escaping at the sink.

(b) What prevents the trap from acting as a siphon within certain limits?

52. Fig. 51 represents two tumblers, *A* containing water and *B* containing some other liquid. Dipping into these liquids are the two ends of an inverted glass U-tube. This tube has a branch tube, *C*, to which is attached a rubber tube, *D*. *E* is a clamp. If air be sucked out of the tube at *D* and the tube be clamped at *E*, liquids will rise in the arms of the glass tube.

(a) What causes the liquids to rise? (b) The heights of the liquid columns *MN* and *OP* are unequal. Why

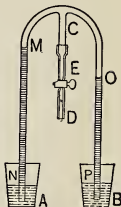


FIG. 51

is this so? (c) Which of the two is the denser liquid?

(d) Having measured the heights of the two liquid columns *MN* and *OP*, how would you compute the specific gravity of the liquid in *B*?

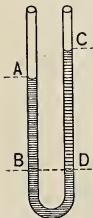


FIG. 52

53. If a glass U-tube (Fig. 52) be partly filled with water and then some kerosene be poured slowly down one of its arms on top of the water, the free surface of the two liquids *A* and *C* will not be on the same level.

(a) Suppose the tube to be of uniform bore, how does the weight of the column of liquid *AB* compare with the weight of the column *CD*? (b) If the height of the column of water *AB* be 14.4 cm. and the height of the column

of kerosene *CD* be 18 cm., what is the specific gravity of kerosene?

CHAPTER III

DYNAMICS

SECTION I

MOTION, VELOCITY, AND ACCELERATION

42. Relative Motion. — *Dynamics* treats of the motion and the tendencies to motion exhibited by matter under the influence of force. Motion is a continuous change of position. A particle of matter can be located in space only by determining its *direction* and *distance* from some other particle, or from some point of reference. Hence, a change of position of a particle must be a change in either direction or distance in relation to some other particle or point of reference. For this reason all motion is spoken of as *relative motion*. A particle moves relatively to a given point when an imaginary straight line connecting it with the point changes in either *direction* or *length*. A particle is at rest relatively to a given point when a straight line joining them changes in *neither* direction *nor* length.

Illustrations. — When you open or shut the legs of a pair of dividers (Fig. 53), the straight line, $a'b'$, connecting the points at the ends of the legs, changes in *length*; hence, there is relative motion between these points. If (Fig. 54) you open the legs a little way and,

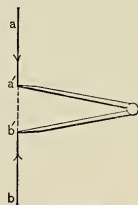


FIG. 53

fixing the end of one of the legs upon a plane surface, trace a circle with the end of the other leg around the former as a center,

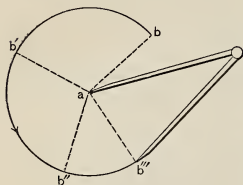


FIG. 54

there will be relative motion between the two points, since a line joining them, ab , ab' , etc., changes in *direction*. If (Fig. 55) you trace with the points of the open dividers two straight parallel lines on a plane surface, the two points will be relatively at rest, just as surely as if the dividers were lying upon the table, since in both cases a straight

line connecting the points ab , $a'b'$, etc., changes in neither length nor direction.

A point may be at the same instant at rest with reference to certain points and in motion with reference to certain other points. For example, while the points of the dividers are tracing straight lines on the plane surface

(Fig. 55) and are relatively at rest, they are in motion with reference to every point in the plane surface.

A passenger in a railway car may be at rest relatively to

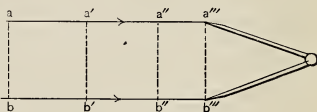


FIG. 55

the car and to the other passengers, but in rapid motion relatively to objects by the roadside. In ordinary language the phrase "a body at rest" means a body that does not change its position with reference to that on which it stands, as, for instance, the surface of the earth or the deck of a ship. It can mean nothing else, for both the body said to be "at rest" and all points on the earth's surface are in rapid motion with reference to the sun and other heavenly bodies, and also with reference to the earth's axis.

43. Velocity. — *Velocity is rate of change of position.* It involves units of distance and units of time, and is commonly expressed in *units of distance per unit of time*,

e.g., meters or feet per second, kilometers or miles per hour, etc.

If the motion of a particle be not uniform, — in other words, if the distances traversed in successive equal times continually increase or continually decrease, — the velocity is said to be *accelerated*. *Acceleration* is the rate at which a particle gains or loses velocity. Every youth is familiar with the acceleration which his toboggan or double runner acquires in descending a hill, also with the retarded motion which a ball experiences when it is rolled along level ground.

Velocity is determined by dividing the distance traversed by the time consumed. If a body move s meters in t seconds, its velocity, v , is $\frac{s}{t}$ meters per second; *i.e.*, $v = \frac{s}{t}$. In case the velocity be not uniform, this result is to be regarded as the *average* velocity for that distance.

The velocity of a body whose motion is not uniform can be given only at some definite instant or at some point in its journey. It denotes the number of units of distance the body *would* traverse in a unit of time in the direction of its motion at that instant, *if its motion were continued unchanged for a whole unit of time*. A velocity possesses direction as well as speed. The term *speed* does not take into account the direction of a motion. If a stone be thrown obliquely upward into the air, both the direction of the motion and the speed continually change.

A shot fired from a gun leaves the muzzle with a definite speed, say 1000 feet per second. At the instant of discharge it is moving in a certain direction, AB (Fig. 56), so that if it continued to

move at that speed for a whole unit of time it would traverse a distance in that direction that may be represented by the length of the line AB . A velocity, then, can be completely represented by a straight line, inasmuch as a straight line has both *magnitude*

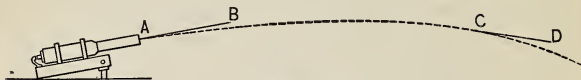


FIG. 56

and *direction*. When the shot reaches the point C it has a different speed and a different direction from that at point A . The velocity at this point may be represented by the line CD . The velocity of the shot is continually changing during its whole flight; this is called *variable velocity*.

When a particle experiences equal changes of speed in equal units of time, its motion is said to be *uniformly accelerated*, and its change of velocity per unit of time is called its *acceleration* and is represented by the letter a . When the velocity increases, as in the case of a falling stone, its acceleration is said to be positive ($+a$); when the velocity decreases, as in the case of a stone thrown upward, its acceleration is said to be negative ($-a$). Negative acceleration is called, in common language, *retardation*.

In the case of a body falling in a vacuum, and in that of a body projected vertically upward, the acceleration is practically uniform. In the former case it is about 9.8 m. (about 32.2 feet) per second; in the latter case it is a negative acceleration of about 9.8 m. per second.

The acceleration of a particle in traversing a certain distance in a given time is found by dividing the entire

change in velocity, v , by the units of time, t , consumed in making the change; *i.e.*, $a = \frac{v}{t}$,

whence, $(1) \ v = at.$

Thus, if the velocity of a railroad train at a certain instant be 15 miles per hour, and half an hour hence it be 25 miles per hour, then the entire change of velocity, v , is 10 miles per hour; hence, the average acceleration, *i.e.*, the acceleration if it were uniformly distributed throughout the 30 minutes, is $\frac{10}{30} = \frac{1}{3}$ of a mile per minute.

44. Formulas for Accelerated Motion. — If a particle starting from a state of rest move with uniform acceleration, a , its velocity, v , at the end of any given number of units of time, t , is found by the equation $(1) \ v = at$, as given in § 43.

From this equation we infer that *change of velocity is proportional to the acceleration and to the time occupied.*

But if a particle be in motion, and at a certain instant have a velocity, V , and its acceleration be a , then its velocity at any subsequent instant is expressed as follows:

After a lapse of one unit of time, $v = V \pm (a \times 1).$

" " " " two units " " $v = V \pm (a \times 2).$

" " " " t " " " $(2) \ v = V \pm at.$

Now, since the velocity of a particle starting from a state of rest increases from zero to at , the average velocity must be $\frac{0 + at}{2} = \frac{1}{2} at$. At this rate, in the same time, t , it would traverse a distance, S , equal to $\frac{1}{2} at \times t = \frac{1}{2} at^2$ units; whence,

$$(3) \ S = \frac{1}{2} at^2,$$

a formula which enables one to compute the entire distance traversed in a given time by a particle starting from a state of rest and having uniformly accelerated motion. It appears that *the entire distance traversed is proportional to the acceleration and to the square of the time occupied.*

If a particle, instead of starting from a state of rest, have an initial velocity V , it would move in t units of time without acceleration a distance $V \times t$; to this distance must be added the distance it moves in consequence of acceleration, in order to obtain the entire distance traversed in t units, and our formula becomes

$$(4) S = Vt + \frac{1}{2} at^2.$$

If it be required to find the distance passed over during any specified unit of time, we may subtract the distance traversed in $t - 1$ units from the distance traversed in t units. Thus, representing the required distance traversed during a specified unit of time, t , by s , we have

$$(5) s = \frac{1}{2} at^2 - \frac{1}{2} a(t - 1)^2 = \frac{1}{2} a(2t - 1).$$

EXERCISES

1. When is there relative motion between two particles?
2. A boy is riding on an electric car along a straight road and his friend on a bicycle regulates his speed so as to keep constantly by his side. Is there relative motion or relative rest between the two?
3. Suppose the two vehicles named in Exercise 2 are turning a curve; are the friends in relative motion or at relative rest?
4. A boat moves away from a wharf at the rate of 5 miles an hour. A person on the boat's deck walks from the prow toward the stern at the rate of 4 miles an hour. (a) What is his rate of motion, i.e., his velocity, with reference to the wharf? (b) What is his velocity with reference to the boat?

5. Illustrate a case in which relative motion and relative rest may occur at the same time.

6. An electric car starts from rest and in 30 seconds has a speed of 1 mile per hour. What is the average acceleration, expressed in feet per second?

7. (a) What is the meaning of the statement that "the velocity of a falling body at the end of the first second of its fall is 32.2 feet per second"? (b) Has the body the same velocity at any other instant?

8. (a) Describe fully the motion of a freely falling body, i.e., a body that meets with no resistance from the air. (b) How does the motion of a body projected vertically upward differ from that of a falling body?

9. (a) What is the velocity of a freely falling body at the end of 1 second when it falls from a state of rest? (b) What is the acceleration of freely falling bodies?

10. The velocity of a particle at a certain instant is V ; its acceleration is a . What will be its velocity, v , after t units of time?

11. If the initial velocity of a body be V , its acceleration a , and its final velocity v , how long, t , was it in acquiring its final velocity?

12. If a body having an initial velocity V acquire in t seconds a velocity v , what is its acceleration?

13. If a body move from a state of rest with a uniform acceleration a , what space, S , will it traverse in t units of time?

14. If a body move from a state of rest with an acceleration a , in what time, t , will it traverse the space S ?

15. The velocity of a particle at a certain instant is 20 feet per second; its acceleration is 3 feet per second. What will be its velocity 10 seconds hence?

16. Suppose that the acceleration of the particle mentioned above be -2 feet per second, what will be its velocity 5 seconds after the instant named?

17. (a) A body falls from a state of rest; its velocity increases (if we disregard the resistance of the air) 9.8 m. per second. What is its velocity at the end of the first second? (b) What at the end of the tenth second? (c) What at the end of $\frac{1}{2}$ of a second?

18. If the initial velocity of a body be 5 feet per second, its final velocity 25 feet per second, and its acceleration 2 feet per second, what was the time consumed in acquiring the final velocity?

19. A bullet is projected vertically upward with an initial velocity of 49 m. per second. What will be its velocity at the end of the third second?

20. How long will the bullet named in the last exercise rise?

21. What velocity will the bullet have at the end of the sixth second, and in what direction will it be moving?

22. A person throws a stone vertically upward to a distance of 78.4 m. With what velocity does the stone leave his hand?

23. Find the depth of a well in which a stone, if dropped, takes $1\frac{1}{2}$ seconds to reach the bottom.

24. A body falls from a state of rest. (a) How many feet does it fall during the fifth second? (b) How many meters does it fall during the fourth second?

25. A stone thrown vertically downward is given an initial velocity of 40 feet per second. How far will it descend in 10 seconds?

26. (a) A bullet is projected vertically upward with an initial velocity of 225.4 feet per second. How long will it rise? (b) How far will it rise?

27. (a) A body falls during 2 seconds. What is its final velocity? (b) How far does it fall?

28. A body falls 297.6 feet in 4 seconds. What was its initial velocity? *Ans.* 10 feet per second.

29. What initial velocity must be given a body that it may rise 6 seconds?

30. A falling body acquires a velocity of 68.6 m. per second. How long does it fall?

31. A body acquires in falling a velocity of 98 m. per second. From what height has it fallen?

SECTION II

COMPOSITION AND RESOLUTION OF VELOCITIES

45. **Composition of Velocities.** — A body may have several velocities in different directions at the same time. For example, a steamer may be moving at the

rate of 8 miles per hour and a person on its deck may be walking toward its prow at the rate of 4 miles per hour. In this case the actual or *resultant* velocity of the person is 12 miles per hour. But if the person walk toward the stern, his resultant velocity is 4 miles per hour.

Now suppose this person walks directly across the vessel from side to side, what will be his resultant velocity? Represent graphically each of his *component* velocities by straight lines on a scale of 1 cm. = 2 miles. Thus, line AB (Fig. 57) may represent his velocity in common with the steamer, and AC his independent velocity. If we complete a parallelogram on these two lines and draw a diagonal, AD , from their junction, this diagonal represents the actual or resultant velocity. For example, if the steamer's course be due north, then the person faces due west as he walks, but his resultant velocity is northwesterly, *i.e.*, in the direction of the line AD . His actual velocity is represented by the length of the line AD . This line measures 4.4 cm.; consequently it represents a velocity, as per scale, of $(4.4 \times 2 =) 8.8$ miles per hour in a direction somewhat north of northwesterly.

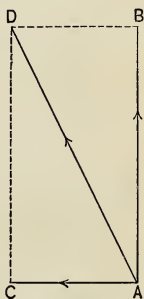


FIG. 57

RULE 1: The resultant of two velocities in the same straight line is the algebraic sum of these velocities.

RULE 2: If two velocities not in the same straight line be represented by the adjacent sides of a parallelogram, their resultant will be represented by the diagonal of the parallelogram drawn from the point of intersection of the two lines.

RULE 3: The resultant of three or more velocities may be found by a repetition of Rule 1 or 2, that is, by first finding the resultant of any two velocities and then the resultant of this resultant and another velocity, and so on.

46. Resolution of Velocities. — *Resolution of Velocities* is the converse of Composition of Velocities. Suppose a car to be ascending a grade at the rate of 8 miles an hour and it be required to find its horizontal and vertical velocities. Let the line AB (Fig. 58) be drawn to represent the grade and velocity on the scale given above. Evidently the lines AC and AD , sides of a parallelogram constructed on line AB as a diagonal, represent to scale the respective velocities required. Lines AC and AD measure, respectively, about 3.5 cm. and 2 cm.; consequently the horizontal and vertical velocities are, respectively, $(3.5 \times 2 =) 7$ miles and $(2 \times 2 =) 4$ miles per hour, approximately.

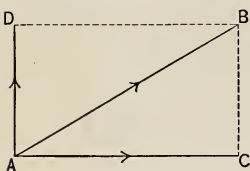


FIG. 58

EXERCISES

1. A steamer is propelled up a stream at the rate of 10 miles per hour relatively to the water. The downward current is flowing with a speed of 40 feet per minute. What is the actual velocity of the boat relatively to the bank?

2. What is the resultant of two velocities of 20 m. and 25 m. per minute whose directions make an angle of 45° ? (Use scale of 1 cm. \approx 5 m.)

3. Find the resultant of the following velocities: 40 m. per second N., 10 m. E., 20 m. S., 45 m. W. Show its direction by a figure.

4. Draw an oblique line to represent a velocity of 50 feet per minute in any southeasterly direction and its corresponding velocities south and east. (Use scale of 1 cm. = 10 feet.)

SECTION III

COMPOSITION AND RESOLUTION OF FORCES

47. **Graphical Representation of Force.** — A force is defined when its *magnitude*, *direction*, and *point of application* are given. We may represent forces graphically by straight lines whose lengths bear to one another the same relation as the numerics of the forces, while the directions of these lines indicate the directions of the forces, and the points from which the lines are drawn indicate the points of application. Thus, on a scale of 1 cm. = 1 kg. the line AB (Fig. 59) represents a force of 3.2 kg. acting toward

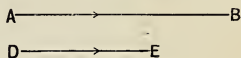


FIG. 59

the right, with its point of application at A ; and the line DE represents a force of 2 kg. acting parallel to the first, with its point of application at D .

48. **Composition of Forces acting in the Same Line; Equilibrium of Forces; Balanced Forces.** — When one force opposes in any degree another force, each is spoken of as a *resistance* to the other. Let f represent the number of pounds of any given force and let a force acting in any given direction be called *positive* and indicated by the plus (+) sign, and a force acting in an opposite direction to the force which we have denominated positive be called *negative* and indicated by the minus (−) sign. Then, if two forces, $+f$ and $-f$, acting on a body at the same point or along the same line be equal, they are said to be *balanced*, and the result is that no change of motion is produced.

Viewed algebraically, $+f - f = 0$; or, correctly interpreted, $+f - f \approx$ (is equivalent to) 0, *i.e.*, no force. In all such cases there is said to be an *equilibrium of forces*, and the body is said to be in a *state of equilibrium*. Equilibrium is the condition of two or more forces which are so opposed that their combined action on a body produces no change in its rest or motion. A force that produces equilibrium with one or more forces is called an *equilibrant*.

49. Unbalanced Forces. — If one of two opposing forces be greater than the other, the excess is spoken of as an *unbalanced force*, and its direction is indicated by one or the other sign, as the case may be. Thus, if a force of + 8 pounds act on a body toward the east, and a force of - 10 pounds act on the same body along the same line, then the unbalanced force is - 2 pounds; *i.e.*, the result is the same as if a single force of 2 pounds acted on the body toward the west. Such an equivalent force is called a *resultant*. *A resultant force is a single force that may be substituted for two or more forces and produce the same result that the simultaneous action of the several forces would produce.*

The resultant of any number of forces acting in the same straight line is equal to the algebraic sum of the forces. An equilibrant of several forces is equal in magnitude to their resultant, but opposite in direction.

An unbalanced force always produces acceleration. Hence, a body acted on by an unbalanced force cannot be at rest, nor can its motion be uniform.

EXERCISES

1. Explain the use of a line to represent a force.
2. (a) When a force of 150 kg. is represented by a line 15 cm. long, what is the scale used? (b) On the same scale, what force will a line 18 cm. long represent? (c) How long should a line be to represent 25 kg.?
3. Three men, A, B, and C, pull on a rope in the same direction with forces, respectively, of 50 pounds, 60 pounds, and 70 pounds. A is nearest the end of the rope, B next, and C next. (a) What is the tension of the rope between A and B? (b) What between B and C? (c) A man, D, just beyond C, pulls with a force of 75 pounds in the opposite direction. With what force must a man, E, pull that there may be equilibrium? (d) When there is equilibrium, what is the tension of the rope between C and D? (e) How great must be the tensile strength of the rope between C and D? (f) Write the equation showing the algebraic addition of the forces in case of equilibrium.
4. The hooks of two spring balances are connected by a string and the balances are pulled. (a) If one registers 5 pounds, what does the other register? (b) What is the tension in the string?
5. How is change of motion produced?
6. What effect does an unbalanced force always produce?

SECTION IV

COMPOSITION OF PARALLEL FORCES—MOMENTS
OF FORCES**50. Composition of Parallel Forces acting in the Same Direction and in the Same Plane.**

Experiment. — AB (Fig. 60) represents a rod in a horizontal position with three strings loosely looped around it so that they may be slid along the rod. Dynamometers are attached to the free ends of the strings. The strings are all stretched in parallel directions in a plane parallel to the top of the table. (Great care

must be taken in the manipulation to keep the three strings exactly parallel. The dynamometers register the tensions in the

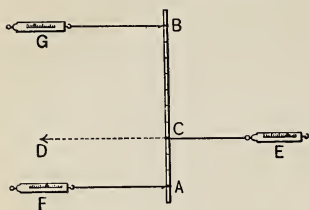


FIG. 60

several strings, *i.e.*, the forces applied through them to the rod.

Observe: (1) When there is equilibrium the dynamometer *E* registers as much as do *F* and *G* added together. But the force applied at *C* is the equilibrant of the other forces, and this is equal to their resultant acting in the direction *CD*. (2) The point of application of the resultant (or equilibrant) is between the points of application of the components. (3) This point is nearer the greater force. (4) The distance of this point from the smaller force is as many times greater than its distance from the larger force as the larger force is times greater than the smaller force. For example, if *AF* be 14 pounds and *BG* be 6 pounds ($14 : 6 = 7 : 3$), then distances *CA* and *CB* will be as $\frac{1}{7} : \frac{1}{3}$. In other words, the component forces are said to *vary inversely as*, or to be *inversely proportional to*, their distances from their resultant. These observations are summarized as follows: The resultant of two parallel forces in the same direction is equal to their sum, and the distances of their points of application from the point of application of the resultant vary inversely as the intensities of the components.

51. Moment of a Force. — The value of a force for producing rotation about a given axis¹ is called its

¹ An axis is a line about which a rotating body turns.

moment with reference to that axis. Point *C* (Fig. 61) may represent the extremity of the axis about which *AB* is supposed to rotate. The perpendicular distance (*CA* or *CB*) from the axis of rota-

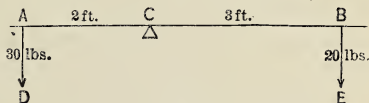


FIG. 61

tion to the line of direction in which a force acts (*AD* or *BE*) is called the *leverage* of the force. We do not speak of the moment of a force in the abstract, but always speak of it with reference to some particular point, which is commonly called the *center of moments*.

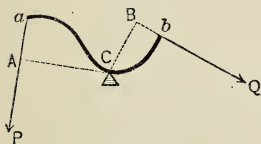


FIG. 62

The moment of a force is measured by the product of the intensity of the force into its leverage. For example, the moment of the force *AD*

(Fig. 61) is expressed numerically by the number ($30 \times 2 =$) 60, and the moment of *BE* is ($20 \times 3 =$) 60. By definition the line *CA* (Fig. 62) is the leverage of the force *aP*, and *CB* of the force *bQ*.

52. Equilibrium of Moments.—The moment of a force is said to be *positive* when it tends to produce right-hand rotation, *i.e.*, rotation in the direction in which the hands of a clock move, and *negative* when its tendency is in the reverse direction. If two forces act at different points of a body which is free to rotate about a fixed axis, they will produce equilibrium when the algebraic sum of their moments is zero. Thus, the moment

of the force applied at A (Fig. 61) is $-(30 \times 2) = -60$. The moment of the force applied at B in an opposite direction is accordingly $+(20 \times 3) = +60$. Their algebraic sum is zero, consequently there is equilibrium between the moments, and no tendency to rotation.

When more than two forces act in this manner there will be equilibrium if the algebraic sum of all the

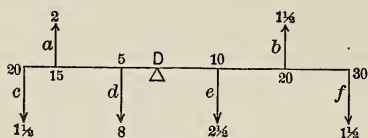


FIG. 63

moments (positive and negative) be zero. Thus, the equation of moments acting about the axis D (Fig. 63) is $([f] 45 + [e] 25 + [a] 30) + ([c] - 30 [d] - 40 [b] - 30) = 0$; the sum of all the moments being zero, there is equilibrium of moments; consequently there is no tendency to rotation.

53. Dynamical Couple. — *Two equal forces applied to the same body in parallel and opposite directions not in the same straight line constitute what is called a dynamical couple. The effect of a couple is to produce rotation, but no motion of translation.*

Since the two forces which constitute a couple are equal and opposite, their resultant is zero, and therefore no single force can equilibrate a couple.

Examples of couples are forces applied to a screw-driver, a watch key, and the milled head of a screw.

54. Moment of a Couple. — The moment of a couple, or its value in producing rotation, is the sum of the moments of its two components about the axis of rotation, or the product of either force by the distance between their directions. Let F and F_1 (Fig. 64) constitute a couple whose points of application are A and B . To find the rotating value of the couple, let P be the axis of rotation; then the moments of F and F_1 relatively to P are $F \times AP$, and $F_1 \times BP$. The total resultant moment of the two forces is $(F \times AP) + (F_1 \times BP)$, or (since $F = F_1$) $F \times AB$.

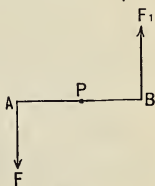


FIG. 64

EXERCISES

1. Two parallel forces of 8 pounds and 12 pounds act in the same direction, respectively, at points A and B , 12 inches apart. Find the magnitude and position of their resultant.

2. Two men carry a weight of 100 pounds suspended from a pole 15 feet long; each man is 18 inches from his end of the pole. Where must the weight be attached in order that one man may bear three fourths of it?

3. (a) A plank weighing 40 pounds is placed across a log so as to be balanced. A boy weighing 60 pounds sits on one end of the plank. Where shall another boy weighing 90 pounds sit that he may balance the first? (b) What pressure will be exerted upon the log?

4. Two horses harnessed abreast are plowing. How can you arrange that one horse shall pull only two thirds as much as the other?

5. The maximum muscular force which a certain man can exert is 200 pounds. With what leverages can he raise a stone weighing a ton?

6. How can pressure be multiplied indefinitely?

7. Three forces of 2, 10, and 12 units act on a body along parallel lines. Show how they may be adjusted so as to be in equilibrium.

SECTION V

CENTER OF GRAVITY

55. Center of Gravity defined. — Let Fig. 65 represent any body of matter, *e.g.*, a stone. Every particle of the



FIG. 65

body is acted upon by the force of gravity. The forces of gravity acting on the particles form a set of parallel forces, the resultant of which equals their sum (§ 50) and has the same downward direction as its components. In whatever position the body may be, the resultant passes through a definite

point; this point is called the *center of gravity* of the body. *The center of gravity (c.g.) of a body is, therefore, the point of application of the resultant of all the forces of gravity; and for many practical purposes the whole weight of the body may be supposed to be concentrated at this point.*

Let G (Fig. 65) represent the c.g. of the stone. For practical purposes we may consider that the force of gravity acts only at this point and in the direction GF . If the stone fall freely, this point cannot deviate from a vertical path, however much other points of the body may rotate about this point during its fall. Inasmuch, then, as the c.g. of a falling body tends to describe a definite path, a line, GF , that represents this path, or the path in which a body supported tends to move, is called the *line of direction*. It may be defined as the straight

line in which lie the c.g. of the body and the c.g. of the earth; its direction is always *vertical*. A vertical line is indicated by a string supporting a small weight, called a *plumb line*. A line or plane perpendicular to a vertical line is *horizontal*.

~ To support any body, then, it is only necessary to provide a support for its c.g. The supporting force must be applied somewhere in the line of direction. The difficulty of poising a book, or any other object, on the end of a finger consists in keeping the support under its c.g., i.e., in the line of direction.

Fig. 66 represents a toy called a "witch," consisting of a cylinder of pith terminating in a hemisphere of lead. The toy will not lie in a horizontal position

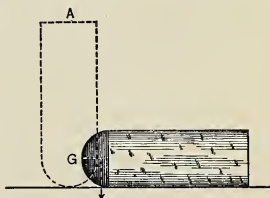


FIG. 66

because when it is horizontal the support is not applied immediately under its c.g. at *G*; but when placed horizontally it immediately assumes a vertical position, *A*.

It appears to rise; really, however, it falls, because its c.g. takes a lower position.

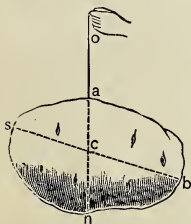


FIG. 67

56. How to find the C.G. of a Body. —

Suspend the body, e.g., a potato, by a string, as in Fig. 67. When the body is at rest there is an equilibrium of forces, and the c.g. must be somewhere in the line of direction *an*. Suspend the body from some other point, as *b*, and the c.g. must be somewhere in the new line of direction *bs*. Since the c.g. lies in both the lines *an* and *bs*, it must be at *c*, their point of intersection. It will be found that, from whatever point the body is supported,

the point c will always be vertically under the point of support. In a similar manner the c.g. of any body may be found. But the c.g. of a body may not be coincident with any particle of the body; for example, the c.g. of a ring, of a hollow sphere, etc., is not within the mass itself.

57. Center of Buoyancy. — The upward pressure against the submerged part of a body floating in a fluid, *e.g.*, the hull of a vessel, is an upward force applied at the c.g. of the displaced fluid. Hence, the c.g. of the displaced fluid is called the *center of buoyancy*.

When the floating body is at rest the center of buoyancy and the c.g. of the body lie in the same vertical

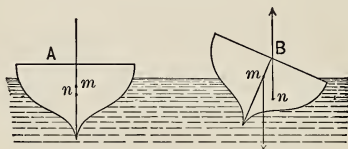


FIG. 68

line, as shown in *A* (Fig. 68), in which m represents the c.g. of a vessel and n the center of buoyancy. If the body be disturbed, as in the rolling of a vessel, the center of buoyancy is shifted, as shown in *B*. In this case the buoyant force of the water acting upward at n and the weight of the body acting downward at m constitute a dynamical couple tending to right the body.

58. Equilibrium of Bodies. — A body will rest in equilibrium when its line of direction passes through its point of support. A body will be supported at its base when its line of direction falls within its base or lowest side.

(The base of any body, *e.g.*, a chair, is the polygon formed by joining by straight lines the points of support.) There are three kinds of equilibrium :

1. A body so supported that when slightly disturbed it tends to return to its original position is said to be in *stable equilibrium*. This will be the case whenever such a disturbance raises its c.g.; for the weight of the body acting at its c.g. tends to bring this point as low as possible, and thus causes it to return to its former position. Evidently a body is in stable equilibrium when the supporting force is applied in the line of direction *above* its c.g.

2. A body so supported that a slight disturbance tends to cause it to take a new position with its c.g. lower than before is in *unstable equilibrium*.

3. A supported body whose c.g. is neither raised nor lowered by a disturbance is in *neutral equilibrium*.

For example, a cylinder, if it be uniformly dense, is in *neutral* equilibrium when placed on its side upon a horizontal plane, and it rests equally well in all positions.

59. Stability of Bodies. — The difficulty of overturning bodies supported at their bases varies with the height

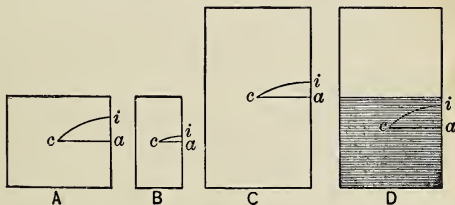


FIG. 69

to which their c.g. must be raised in overturning them. The letter *c* (Fig. 69) marks the position of the c.g. of each of the four bodies *A*, *B*, *C*, and *D*. If any one of

these bodies be overturned, its c.g. must pass through the arc ci , and be raised through the height ai . By comparing A with B and supposing them to be of equal weight, we learn that *in overturning two bodies of equal weight and height of c.g., the c.g. of that body which has the larger base must be raised higher, and that body is, therefore, overturned with greater difficulty.* A comparison of A and C , supposing them to be of equal weight, shows that *when two bodies have equal bases and weights the body having its c.g. higher is more easily overturned.* D and C have equal weights, bases, and heights, but D is made heavy at the bottom, and this *lowers its c.g. and gives it greater stability.*

60. Weight of a Lever. — In practice we consider that the weight of a body is located at its c.g. (§ 55). For example, let AB (Fig. 70) represent a plank weighing 20 kg., resting on a prop at C . Its c.g. is at D . We

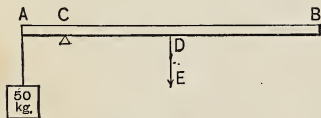


FIG. 70

have then to consider a force of 20 kg. applied at D in the direction DE . Let the distance AC be 10 dm. and the distance DC be 25 dm.

Then the moment of the weight of the plank located at D is $(20 \times 25 =) 500$. To produce equilibrium a force of $(500 \div 10 =) 50$ kg. must be applied at A .

The plank in this case is regarded as a lever. It is evident that when precise results are required the weight of the lever must be taken into account. What is the pressure on the prop C in this case?

EXERCISES

1. In which of the following cases does the c.g. lie inside, and in which outside, the body: a straight wire, the same wire bent into a circle, a tumbler, a baseball, a football?

2. Why is a pyramid a very stable structure?

3. What is the object of ballast in a vessel?

4. State several ways of giving stability to an inkstand.

5. (a) In what position would you place a cone on a horizontal plane that it may be in stable equilibrium? (b) that it may be in neutral equilibrium? (c) that it may be in unstable equilibrium?



FIG. 72

6. In loading a wagon where should the heavy luggage be placed? Why?

7. Why are bipeds slower in learning to walk than quadrupeds?

8. Why is mercury placed in the bulb of a hydrometer?

9. How will a man by rising in a boat affect its stability?

10. Which is more liable to be overturned, a load of hay or a load of stone of equal weight?

11. What attitude does a man assume when carrying a heavy load on his back? Why?

12. What position do bodies floating in air or in water take?

13. (a) Explain how the toy horse (Fig. 71) stands upon the platform without falling off. (b) Explain how the toy may rock upon its support without falling off.



FIG. 71

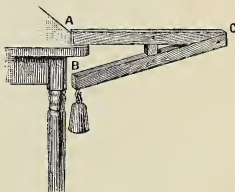


FIG. 73

14. It is difficult to balance a lead pencil on the end of a finger; but by attaching two knives to it, as in Fig. 72, it may be rocked to and fro without falling. Explain.

15. If the end C of the triangular frame AB (Fig. 73) be raised and allowed to fall, the frame will rock to and fro on its support and finally come to rest in its original position. (a) What kind of equilibrium has it? (b) If the weight at the end B be removed, will the frame be supported by the table? (c) Why?

16. Suppose the distance CB (Fig. 70) to be 40 dm., the weight applied at A to be 100 kg., and the other conditions be the same as given in § 60, what force applied at B will produce equilibrium?

SECTION VI

COMPOSITION OF FORCES THAT ARE NOT PARALLEL

61. **Parallelogram of Forces.**—If two forces whose lines of action pass through the same point act simultaneously at an angle with each other, then their resultant (or equilibrant) may be ascertained by means of the *parallelogram of forces*, as the following experiment will illustrate.

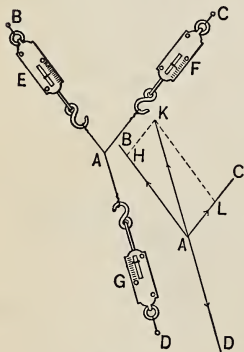


FIG. 74

Experiment.—Stretch over a sheet of white paper three spring balances E , F , and G (Fig. 74) with strings meeting at a common point, A . Drive nails at B , C , and D so as to hold the balances taut. Place a block with a straight edge against each string and draw lines on the paper showing the directions in

which the several forces act. Note the readings of E , F , and G , which in this case we suppose to be, respectively, 30, 13, and 34.

Remove the balances, and on some convenient scale lay off on AB , AC , and AD distances to represent the corresponding forces. Complete the parallelogram $AHKL$ and draw the diagonal AK . Measure this diagonal, and if the work has been carefully done, it will be found that AK and AD are in the same straight line and equal in length. But AD is the equilibrant of the forces AH and AL ; then AK , which is equal and opposite to AD , must be the *resultant* of forces AH and AL .

LAW: If two forces acting simultaneously on a body be represented by the adjacent sides of a parallelogram, their resultant is represented by the diagonal which passes through the intersection of those sides.

Let two forces in a plane applied at points A and B of a stone (Fig. 75) act in the directions AC and BD , respectively. The

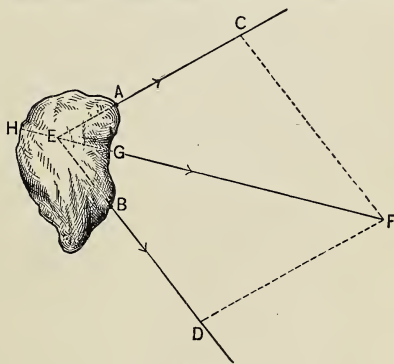


FIG. 75

direction of the resultant must pass through E , the point where the lines of direction of the given forces when produced backward intersect. If, now, the lines EC and ED be laid off to represent the relative intensities of the forces, the diagonal EF of the parallelogram constructed thereon will represent their resultant, and its point of application may be G or any other point in the line GH .

62. Composition of More than Two Forces in the Same Plane. — *When more than two components are given, find the resultant of any two of them, then that of this resultant and a third, and so on, till every component has been used.* Thus, in Fig. 76, AC is the resultant of AB and AD , and AF is the resultant of AC and AE , i.e., of the three forces AB , AD , and AE .

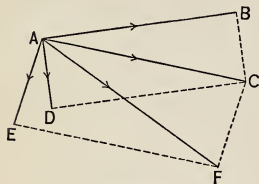


FIG. 76

63. Resolution of a Force. — A single force may be resolved into two or more component forces acting at angles to one another. We may take, for illustration, a body, B (Fig. 77), supported on an inclined plane, MN . Let the vertical line AW represent the weight W of the body, whose point of application is at A , its c.g. Construct the parallelogram $ACWD$, and the component AD represents the force F , which tends to move the body down the plane, to prevent which requires (friction between the body and the plane being disregarded¹) a force equal to F acting in the opposite direction, e.g., the weight S . Component AC represents the pressure P of the body upon the plane.

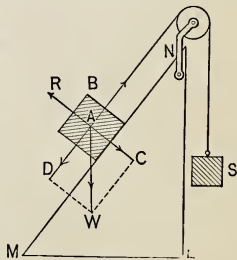


FIG. 77

¹ In practice there is always more or less friction, which assists in the support of the body on the plane.

The triangles AWD and NML are equiangular and therefore similar.

Hence, (1) $\frac{AD}{AW} = \frac{NL}{NM}$, or $\frac{F}{W} = \frac{\text{height of plane}}{\text{length of plane}}$;

also, (2) $\frac{WD \text{ (or } AC)}{AW} = \frac{ML}{NM}$, or $\frac{P}{W} = \frac{\text{length of base}}{\text{length of plane}}$.

Formula (1) translated gives us the following important law for the simple machine called the inclined plane: When a given force acts parallel to an inclined plane it will support a weight as many times itself as the length of the plane is times its vertical height.

EXERCISES

1. What is the greatest and what the least resultant of two forces of 15 pounds and 17 pounds?

2. Draw on paper pairs of lines making about the same angles with each other as AB and AC in the four diagrams (Fig. 78), and having

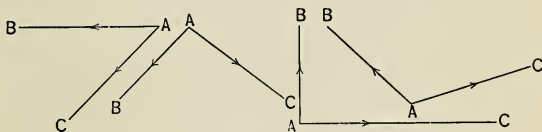


FIG. 78

about the same directions; assign numerical values arbitrarily to each component, drawing to scale, and find the direction and the numerical value of the resultant of each pair of components.

3. Two forces of 20 pounds and 30 pounds act at an angle of 90° . Find the intensity of their resultant without constructing a parallelogram.

4. Resolve a force of 40 pounds into two components at right angles to each other, one of the forces to be 15 pounds.

5. (a) The base of an inclined plane is 12 feet, its height 5 feet, and its length 13 feet. What force acting parallel to the plane will support on it a weight of 300 pounds? (b) What will be the pressure on the plane?

6. What force parallel to an inclined plane 50 feet long and 25 feet high will support on the plane a body weighing a ton?

SECTION VII

NEWTON'S THREE LAWS OF MOTION—MOMENTUM

The effects of impressed force on the motions of bodies are concisely expressed in what are known as *The Three Laws of Motion*, first enunciated by Sir Isaac Newton.

64. Newton's First Law of Motion; Inertia.—A body at rest remains at rest, and a body in motion moves with uniform speed in a straight line, unless acted upon by some external force. This law is an *axiom*; it does not admit of, and does not require, *direct* experimental proof; its truth is universally admitted by all who thoroughly understand its import.

It is directly deduced from the fundamental fact that "every effect requires a cause to produce it." Hence, a body unaffected by any force must remain in the state in which it already exists. By the phrase "unless acted upon by some external force" Newton means that the action must be between the body under consideration and some other body, in contradistinction to an action between parts of the same body.

Prior to Newton's time (1642-1727) Copernicus had demonstrated that the whole solar system revolves about a common center; but he failed to point out what it is that keeps the

planets in motion.¹ Newton, in the law given above, showed that a *moving body "left to itself" does not require any force to keep it in motion.* If no force act on such a body, it moves at a uniform rate in a straight line. It is only when the direction or the speed of the body is altered that we know that force is at work; so that the only force required in the case of the planets is one (gravity) to bend or alter the direction of motion.

This law is also known as the *Law of Inertia*, since it states that no body is capable of altering its state of rest or motion without the intervention of some outside influence. We state this fact briefly when we say that *every body has inertia.*

Inertia is the Latin word for "laziness"; but laziness in matter is manifested quite as much in its indisposition to stop when in motion as to move when at rest. The state of motion is quite as natural to matter as the state of rest.

Examples of Inertia.— In a railway collision the rear cars maintain their inertia of motion and act like battering-rams on the cars in front of them. The body of a person stepping off a moving car retains the motion it had when on the car; his feet are stopped as they touch the ground, but the rest of his body falls forward unless the person steps lively. (In what direction ought he to step?) A tablecloth may be so quickly drawn from a table as to leave all the dishes, in consequence of their inertia of rest, occupying nearly the same relative positions that they

¹ Kepler, who followed Copernicus, attempted an explanation. His thought was pretty nearly this: that the rays of the sun were like the spokes of a wheel, and that they caught the planets and carried them round. A little later Descartes propounded a theory that maintained its ground for a very long time and, strange to say, was the theory advanced in a text-book in use in one of our American colleges as late as 1743. He accounted for the planetary motions by his "system of vortices." Water moving round and round in a whirlpool will carry with it light bodies, such as straws and chips of wood. He supposed that a vortex or swirl of air or ether revolving about the sun carried the planets with it round and round in a similar manner.

had before the cloth was withdrawn. When a carpet is beaten the carpet is propelled forward, but the dust lags behind. When water flowing in pipes is suddenly turned off, the shock produced sometimes bursts the pipes. It is only on the assumption of the correctness of the Law of Inertia that it becomes possible to calculate the times of eclipses and of tides, the different phases of the moon, and the motions of celestial bodies generally, as given in almanacs.

“Uniform velocity” in the case of bodies is nowhere found in nature. Moving bodies always meet with resistances, that is, they are always acted on by external forces; but the more the resistances are removed, the more nearly uniform is every motion. If a stone were thrown along a surface of perfectly smooth ice without encountering any resistance from friction or from the air, its motion would be uniform and “in a straight line.”

65. Momentum. — If two bodies, one of which contains twice as much matter as the other, move with equal velocities, it will require twice as great a force to stop the more massive body as to stop the other in the same time; or the same force will require twice as long a time. Hence, we conclude that of two bodies moving with the same velocity the body that has twice the mass has twice the “quantity of motion,” or, in scientific language, twice the *momentum*. Momentum is not velocity, but involves both mass and velocity. A moving point has velocity but not momentum.

The momentum of a body is a quantity measured by the product of its mass and its velocity. A unit of momentum is the momentum of a unit mass moving with a

unit velocity. If a body contains 80 g. of matter and moves at the rate of 100 cm. per second, it has 8000 units of momentum.

66. Newton's Second Law. — Change of momentum takes place in the direction in which the force acts, and is proportional to its intensity and to the time during which it acts.

The first law stated that force alone can produce a change of motion; the second law tells us how the change depends on the *magnitude* and the *direction* of the force.

This law (except as regards direction) is expressed in the following formula: $ft = mv$, in which m is the mass of the body, v the change of velocity, mv the change of momentum, f the force that produces the change, and t the time during which the change is made.

The product ft signifies that change of momentum is proportional to the time, t , during which a force acts and to the intensity, f , of the force. We infer from this equation (1) that *a definite force acting upon any free body for a given time will cause a change of velocity which is inversely proportional to its mass.* This law declares, by implication,¹ (2) that *an unbalanced force always produces in a given time exactly the same change of momentum, regardless of the mass of the body; that an unbalanced force never fails to produce a change of momentum; and hence that any force, however small, can move any free body, of however great mass.*

For example, a child can move a free body having a mass of a ton, and the momentum that the child can generate in this

¹ No reference is made in the law to the *mass* of the body acted upon.

immense body in a given time is precisely the same as that which he would generate by the exertion of the same force for the same length of time on a body having a mass of, say, 10 pounds. Momentum is the product of mass by velocity; so, of course, as the mass is large, the velocity acquired in a given time will be correspondingly small. The instant the child begins to act, the immense body begins to move. Its velocity, infinitesimally small at the beginning, increases at an almost infinitesimally slow rate, so that it might be many minutes before its motion would become perceptible.

This law declares, by implication, (3) that *a force acting on a body in motion produces just the same effect as if it were acting on the same body at rest*, for no reference is made in the law to the *state* of the body acted upon.

Experiment. — Draw back the rod *D* (Fig. 79) toward the left, and place the detent pin *c* in one of the slots. Place one of the brass balls on the projecting rod in contact with the end of

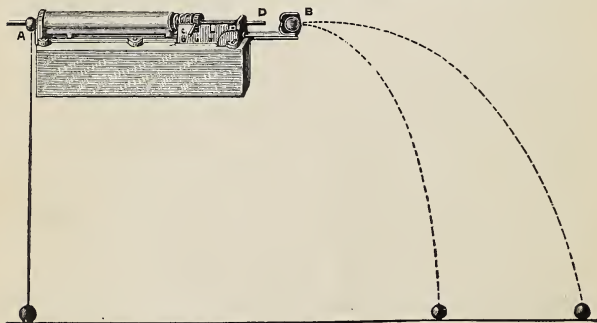


FIG. 79

the instrument, as at *A*. Place the other ball in the short tube *B*. Raise the apparatus to as great an elevation as practicable, and place it in a perfectly horizontal position. Release the detent,

and the rod, propelled by the elastic force of the spring within, will strike the ball *B*, projecting it in a horizontal direction. At the same instant that *B* leaves the tube and is free to fall, the ball *A* is released from the rod and begins to fall. The sounds made on striking the floor reach the ears of the observer at the same instant; this shows that both balls reach the floor in sensibly the same time, and that the horizontal motion which one of the balls has does not affect the time of its fall, *i.e.*, does not modify the effect of the force of gravity.¹

67. Newton's Third Law. — To every action there is an equal and opposite reaction.

This law virtually states that all forces are of the nature of a stress (§ 12) or a reciprocal action between portions of matter. We are accustomed to say that one of two bodies *acts* upon the other, and the latter *reacts* upon the former.

Every action is either a *pull* or a *push*. We cannot conceive of a pull or a push except between at least two bodies or two parts of the same body; there is no such thing as a one-sided pull or push. As the Chinese proverb declares, "You can't clap hands with one hand." The wings of a bird act upon the air, giving a certain portion of it a rearward motion; the air reacts upon the wings, giving the bird a forward motion. The bat strikes the ball, imparting to it an acceleration; the ball reacts upon the bat, giving it a negative acceleration.

If action and reaction were not equal, there might be a possibility that a person standing in a basket might raise himself by

¹ This principle of the independence of forces acting simultaneously was an experimental discovery made by Galileo. Before his time it was held that one cause must cease to act before another can commence to do so; and, accordingly, it was believed that when a projectile was shot into the air the force of projection must be expended before any tendency to fall could assert itself. In reality, however, after a projectile leaves the muzzle of a gun it is unsupported, no amount of velocity in a horizontal direction furnishing any support; consequently the projectile must begin to fall the moment it leaves the muzzle.

pulling on the handles, that a vessel might be propelled in a calm by blowing against its sail with a powerful bellows fixed to the deck of the same vessel, that a person sitting in a buggy might give himself a ride by pressing his feet against the dasher, that a person might advance without pressing the earth beneath him, or that a bird might fly without having the external air to act upon.

Appearances sometimes seem to contradict the above statements. For example, a man standing on a wharf pulls a distant boat by means of a rope. The boat moves as the result of the pull, but, though he is bracing himself against the wharf, he is not willing, perhaps, to concede that he is likewise pulled. Let him stand in the boat and pull the rope which is attached at the other end to the wharf; both he and the boat move. What body, according to *appearances*, is pulled in this case? What bodies are *actually* pulled?

A very instructive illustration of the principle of reaction is furnished by the following experiment: Suspend by a strong sewing thread, *A* (Fig. 80), a metal ball, *B*, weighing from 5 to 10 pounds. To the lower side of the ball attach another thread, *C*, of the same kind. Now either of the two threads may be broken at will. If, grasping the lower thread at *C*, you pull gently and gradually increase the pull, the upper thread will break, because, in addition to your pull, it is pulled by the weight of the ball, while the lower thread is affected only by the pull of the hand. But if you pull the lower thread with a sudden jerk, the reaction of the ball due to its inertia will cause the lower thread to break.



FIG. 80

In the case of action between two free bodies, the law implies that the *momenta* generated by the action and by the reaction are equal. The recoil of a rifle affords a good illustration of this. The gases liberated by the explosion of the powder inside the barrel exert equal and opposite impulses on the ball and on the

gun, and cause them to move in opposite directions with equal momenta. Hence, if the speed of the recoil of the rifle be known, the speed of the ball can be computed, and *vice versa*.

For example, let the masses of the rifle and the ball be, respectively, 5 pounds and 1 ounce, and the maximum velocity of the rifle be 10 feet per second. Then the momentum of the rifle at the instant is $(5 \times 10 =)$ 50 units. But the momentum of the ball at the same instant is also 50 units. Hence, $(50 \div \frac{1}{16} =)$ 800 feet per second is the maximum velocity of the ball.

EXERCISES

1. Why does not a pendulum bob stop when it reaches the lowest point of its arc?

2. How do you explain the fact that a circus rider leaps through a hoop and lands on the horse's back some distance beyond by simply jumping vertically upward?

3. How are we made aware of the existence of force?

4. Is perpetual motion possible?

5. A carriage is suddenly stopped, and the passengers are said to be "thrown out." Are they *thrown*?

6. (a) Why may a man raise himself by pulling on a horizontal bar, but not by pulling on any part of his person? (b) In which case is he acted upon by an external force? (c) In the first case, which body receives the *action* and which the *reaction*? (d) State what receives the action in the second case, and what receives the reaction.

7. When do action and reaction neutralize each other and have no tendency to produce a change of motion?

8. What agent is the immediate cause of motion?

9. What distinction do you make between velocity and momentum?

10. Upon what does the momentum given to a ball fired from a gun by the expanding gases depend?

11. Inasmuch as the ball and the gun mentioned in Exercise 10 are affected by equal forces and for the same length of time, how will the momenta communicated to the two compare?

12. If there be 25 pounds of matter in the gun and 1 ounce ($\frac{1}{16}$ lb.) in the ball, and the gun acquire a maximum velocity of 3 feet per second, what, at that instant, is the velocity of the ball?

13. Can any body be put in motion in no time, *i.e.*, does it require time to change the motion of a body? (Demonstrate from formula $ft = mv$.)

14. Compare the momentum of a car weighing 50 tons, moving 10 feet per minute, with that of a lump of ice weighing 5 hundred-weight, at the end of the third second of its fall.

15. With what velocity must a boy weighing 25 kg. move to have the same momentum that a man weighing 80 kg. has when running at the rate of 10 km. per hour?

16. Since $ft = mv$, to what is change of momentum proportional?

17. If the same force act for the same length of time upon bodies having different masses, to what will the velocities produced be proportional?

18. Two boats of unequal masses are brought together by pulling on a rope. (a) Resistance being disregarded, how will their momenta at any given instant compare? (b) How will their velocities at the same instants compare?

19. If the motion of the moon in its orbit about the earth were to cease, these bodies would approach each other. The mass of the earth is about 80 times that of the moon. What part of the whole distance between them would the moon move before collision?

20. (a) Why does not a given force, acting for a given length of time, give a loaded car as great a velocity as an empty car? (b) After equal forces have acted for the same length of time upon both cars, and have given them unequal velocities, which will be the more difficult to stop?

21. (a) The planets move unceasingly; is this evidence that there are forces pushing or pulling them along? (b) None of their motions are in straight lines; are they acted upon by external forces?

22. A certain body is in motion. Suppose that all hindrances to motion and all external forces be withdrawn from it, how long will it move? Why? In what direction? Why? With what kind of motion, *i.e.*, accelerated, retarded, or uniform? Why?

23. If one body have four times the mass of another, how must the forces applied to them compare in order to give them equal momenta in equal times?

24. Explain the tendency of a person standing in a car to fall, and state the direction of the fall, both when the car suddenly starts and when it stops.

25. Which law of motion is illustrated by the "kick" of a gun?

26. How can you tell, by pushing, which of two boxes is full of sand and which is empty?

27. If a person sitting in a swing throw a heavy weight horizontally, how is he affected thereby? Explain.

28. (a) Where will a bullet dropped from the ceiling of a railway car moving with a uniform velocity of 50 miles an hour strike the floor? (b) Will the path of its fall be vertical?

SECTION VIII

MEASUREMENT OF FORCE IN ABSOLUTE UNITS

68. **Constant Force.** — A constant force is a force that acts continuously and with uniform intensity. Such a force is gravity. We have seen in the case of falling bodies that *a constant force acting on a free body produces uniformly accelerated motion.*

69. **Measurement of Force in Terms of Mass and Acceleration.** — Force is known to exist only by its effects; hence, it can be measured only by measuring its effects. Newton's Second Law of Motion teaches how force may be measured. We learn from this law that force tends to produce a change of momentum. From the formula

(§ 66) $ft = mv$ we obtain $f = \frac{mv}{t}$. From the latter for-

mula we infer that force is measured by the quotient $\frac{mv}{t}$, in other words, by the change of momentum it is capable

of producing in its line of action per unit of time. But change of velocity per unit of time (i.e., $\frac{v}{t}$) is represented by a ; hence, $f = \frac{mv}{t} = ma$.

If the factors m , v , and t are each equal to 1, then the force is equal to 1. A unit force, therefore, is a force which, acting for a unit of time, will give to a unit mass a unit velocity. A constant force of the requisite intensity to produce in a gram-mass a change of velocity of 1 cm. per second, i.e., an acceleration of 1 cm., is called a *dyne*. The dyne is independent of the force of gravity; hence, it is called an *absolute* unit of force. (In this connection § 15 should be reviewed.)

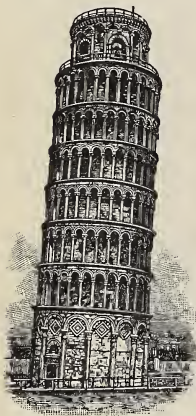
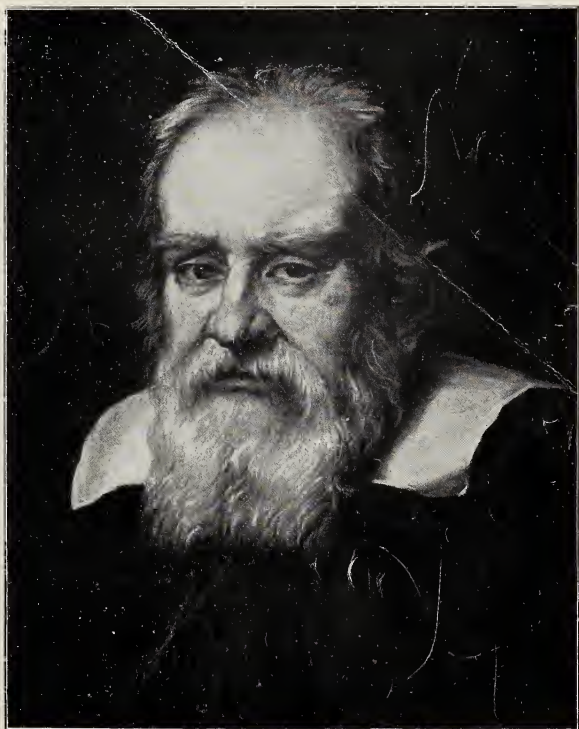


FIG. 81

Any mass falling freely receives at Paris an acceleration of 980.96 cm. per second; at Boston, 980.4 cm. Consequently a gram-mass weighs at Paris 980.96 dynes; at Boston, 980.4 dynes. The letter g is usually substituted for a in representing the acceleration produced by the force of gravity at any given locality; so we say, in general, that the weight of a gram-mass is g dynes.

It is apparent that mass, force, and rate of change of velocity, or acceleration, are quantities closely related to one another. If we wish to measure mass, we can do so by calculating the



GALILEO (1564-1642)

Mathematician, astronomer, physicist, "founder of experimental science."
Portrait after painting by Sustermans, in the Uffizi Gallery, Florence.

acceleration which would be imparted to it by a given force; if we wish to measure force, we calculate the acceleration which it would impart to a given mass.

70. Galileo's Experiment with Falling Bodies. — Galileo let fall from the top of the leaning tower at Pisa¹ iron balls of widely different masses, and found that they reached the ground at apparently the same instant.

This celebrated experiment established the important fact that *the acceleration of a falling body due to the force of gravity is independent of its mass.*

This proposition is apparently contradicted by everyday experience, for if a coin and a feather be dropped from a height, they fall with very different velocities. But if a coin and a feather be placed in a long glass tube (Fig. 82), the air exhausted, and the tube turned end for end, it will be found that the coin and the feather fall in the vacuum with equal velocities. It is evident, then, that when there is a difference in the acceleration of falling bodies at the same place it is due not to the force of gravitation, but to some other influence, for example, the resistance of the air.²



FIG. 82

EXERCISES

1. (a) Can the masses of two bodies at different altitudes and latitudes be compared by using the same spring balance at the different places? (b) Can the masses of two bodies be compared by weighing with a trip balance without knowing the force of gravity at the place?

¹ This building (Fig. 81), consisting of a series of open galleries one above another, reaching to a total height of 179 feet, is admirably adapted to the purpose here mentioned.

² The investigation by Galileo of the motion of falling bodies was one of the first steps in the development of modern science.

2. What part of a gram-force is a dyne?
3. Define a gram-force and a dyne.
4. A constant force acting on a free body produces what effect?
5. To what is the acceleration produced in equal masses proportional; *i.e.*, if m is constant, a will vary as what?
6. On what condition will equal forces produce equal accelerations?
7. Suppose that you fill a box with sand, place it on a toy cart, pull the cart by a string with a constant force along a smooth floor for a certain number of seconds, and observe the acceleration given the load (cart, box, and sand), then remove the sand and replace it with lead shot. How can you tell, by pulling the load with the same force as before, when it has the same mass as the former load?
8. (a) When we speak of a force of 1 pound what do we mean? (b) When we speak of a force of 1 dyne what do we mean? (c) When we speak of a mass of 1 pound what do we mean?
9. (a) If one mass be four times another, how many times as much force is necessary to produce the same acceleration in the former as in the latter? (b) How many times greater is the force of gravity acting on a mass of 100 pounds than that acting on a mass of 1 pound? (c) If a 100-pound iron ball and a 1-pound iron ball be let drop from the same height at the same instant, which ought to reach the ground first?
10. A mass of 4 g. is moving with an acceleration of 12 cm. per second. What is the force acting?
11. A body acted on by a force of 100 dynes receives an acceleration of 20 cm. per second. What is its mass?
12. A mass of 30 g. is moved by a constant force of 50 dynes. What is its acceleration?
13. What acceleration will a force of 20 dynes produce on a mass of 10 g.?
14. A mass of 4 kg. falls freely. What is the value of the force acting upon it?

$$\begin{aligned}
 \text{Solution: } f &= ma \\
 &= 4000 \times 980 \\
 &= 392 \times 10^4 \text{ dynes.}
 \end{aligned}$$

ball, having no force operating to change its motion, continues in the direction in which it is moving at that point, *i.e.*, in the direction *ih*, which is tangent to its former circular path.

If the free end of the string be held in the hand, the ball while revolving about the hand appears to pull the hand. But it is evident that this is due to the *reaction* of the force exerted by the hand on the ball. This reaction is commonly called *centrifugal force*.

72. Law of Centripetal Force. — Tie the end of a string to a stone. Whirl it around your hand, and feel the pull. How great is the pull? You will discover that it depends on *the mass of the stone, the length of the string, and the swiftness of the whirl*. Suppose the stone to be as massive as the earth, the length of the string to be equal to the earth's distance from the sun, and the swiftness of its motion to be the speed of the earth in its orbit. The pull then would represent the gravitation stress that holds the earth in its orbit about the sun.

LAW: For a body moving in a circular orbit, the centripetal force is proportional to the mass of the body and to the square of its velocity, and inversely proportional to its distance from the center of motion.

Let f represent the centripetal force, m the mass of the revolving body, v its velocity, and r the radius of the circle, and the law may be expressed in the following formula:

$$f = \frac{mv^2}{r}.$$

The farther a point is from the axis of motion, the farther it has to move during a rotation; consequently the greater must be its velocity to complete a revolution in a given time.

Bodies at the equator are farthest removed from the earth's axis and have the greatest velocity due to the rotation of the earth; consequently they have the greatest tendency to fly off from its surface. The effect of this is to counteract, in some measure, the force of gravity and thus diminish the apparent weight of bodies. It is calculated that a body weighs about $\frac{1}{289}$ less at the equator than at either pole, in consequence of the greater tangential tendency at the former place. But 289 is the square of 17; hence, if the earth's velocity were increased seventeenfold, objects at the equator would weigh nothing.

R (Fig. 84) represents a rotating apparatus on which is mounted a glass globe, *G*, containing a quantity of colored liquid. When

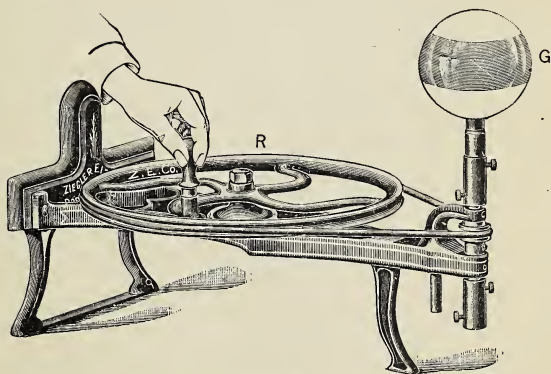


FIG. 84

the globe is rotated the liquid gradually rises and forms an equatorial ring within the globe, leaving the bottom dry. In a similar manner the water of the earth's great ocean is "heaped up" at

the equator. If the earth were to cease to rotate, the water at the equator would flow toward the polar regions, forming two grand polar oceans separated by a belt of land at the equator.

If the globe G (Fig. 84) contain liquids of different densities, when it is rotated the liquids will form concentric rings in the order of their densities. The densest liquid will have the greatest tangential tendency, as may be inferred from the law given above ; consequently it will form the outer ring. It is on this principle that *cream separators* are operated. The milk is caused to rotate rapidly in the separator, the rotation separating the heavier "skimmed" milk that forms the outer layer from the lighter cream that forms the inner layer. Provision is made at the proper time for drawing off each liquid while in motion into separate vessels.¹

In public laundries clothes are dried independently of the weather by being placed in wire cages and rotated with great speed ; the water is separated from the clothes in much the same manner as mud is separated from a rotating carriage wheel.

When a grindstone in a machine shop, or the fly wheel of a steam engine, is made to rotate so fast that the cohesion of its parts is no longer able to keep them moving in their circular paths, it "bursts" and the fragments fly off tangentially with great velocity.

EXERCISES

1. (a) What is the cause of the stretching force exerted on the rubber cord when you swing a return ball about your hand ? (b) Suppose that you double the velocity of the ball, how many times do you increase this stretching force ?

2. Why do wheels and grindstones, when rapidly rotating, tend to break, and the pieces to fly off ?

3. On what does the magnitude of the pull between a rotating body and its center of motion depend ?

¹ By this process there is not only a great gain in the freshness of the products obtained but also in the matter of time, for a more complete separation is effected in a few minutes than can be accomplished in many hours by the old-time method of leaving the cream to "rise."

4. (a) Explain the danger that a carriage will be overturned in turning a corner. (b) How many fold is the tendency to overturn increased by doubling the velocity of the carriage?

5. Account for the *curvilinear* orbits of the planets.

6. What is the centripetal force in planetary motions?

7. In what way should the rails be laid in order to neutralize the tangential tendency of a railway train when going around a curve?

8. In what way is the weight of terrestrial bodies nullified in some degree by the earth's motion?

SECTION X

GRAVITATION

73. Gravitation is Universal. — We know that we ourselves and objects about us are pulled toward the earth by a force (weight) which is called (the Latin expression employed by Newton was *gravitas*) *gravity*. Sir Isaac Newton was the first to show that this force, better called *stress*, exists between bodies separated by any distance, however great; in other words, that *there is a stress between every body of matter in the universe and every other body*.

The force which causes a body to fall to the ground is none other than that which continually compels the moon to accompany the earth in its path around the sun, and which keeps the earth itself from fleeing off into space, away from the sun. This mutual action which exists between all bodies is called *universal gravitation*. Newton discovered the law which expresses the character of this action. *Why* bodies attract one another, however, is as much a mystery as ever.

74. Law of Gravitation. — The Law of Universal Gravitation is as follows:

The gravitation stress between every two particles of matter in the universe varies directly as the product of their masses, and inversely as the square of the distance between them.

If the masses of two particles be represented by m and m' , the distance between their centers of gravity by d , and the gravitation stress by f , this relation is expressed mathematically thus:

$$(1) f \propto \frac{mm'}{d^2}.$$

For example, if the mass of either particle be doubled, the product (mm') of the masses is doubled, and consequently the stress is doubled. If the distance between them be doubled, then $\left(\frac{1}{2^2} = \frac{1}{4}\right)$ the stress becomes one fourth as great.

75. Law of Weight. — The term *weight* is restricted in its application. It is applied only to *the force with which terrestrial bodies are drawn to the earth*. Since the masses of both the body and the earth are supposed to remain the same, in applying the law of gravitation for the determination of the relative weights of the same body at different localities, the masses of both bodies are disregarded, and formula (1) becomes, substituting w (weight) for f ,

$$(2) w \approx \frac{1}{d^2};$$

or, expressed in a more practical form,

$$(3) w : w' :: \frac{1}{d^2} : \frac{1}{d'^2},$$

in which d and d' represent different distances from the earth's center and w and w' represent the corresponding weights of the body at the different localities.

The same may be expressed in the form of a law as follows:

The weight of a body at or above the surface of the earth varies inversely as the square of the distance from the center of the earth.

Since the earth is not a perfect sphere,¹ it follows, from the law, that the weight of the same body differs at different places on the earth's surface. Its loss of weight in being transported from the poles to the equator, due to the increase of distance from the center of the earth, is estimated to be $\frac{1}{568}$ of its weight at the poles. But we have previously seen (§ 72) that the tangential tendency at the equator diminishes the weight of a body $\frac{1}{289}$. Now in consequence of difference in distance from the center of the earth and difference in velocity due to the earth's rotation, a body weighs at the equator ($\frac{1}{568} + \frac{1}{289} =$) $\frac{1}{192}$ less than at the poles.

We learn from the law of weight that a body weighs more at the earth's surface than above it; in other words, bodies become lighter as they are raised above the earth's surface. But since the force diminishes as the square of the distance from the center (not from the surface) of the earth, and since the surface is about 4000 miles from the center, the diminution for a few miles or for any distance which we are able to raise bodies is scarcely perceptible; hence, in all commercial transactions we may, without important error, buy and sell as if the weighing always took place at the same distance from the center of the earth, in which case mass is strictly proportional to weight (§ 7).

EXERCISES

1. (a) Which is independent of mass, weight or the acceleration due to the earth's attraction? (b) Which varies as the mass?

¹ The earth is a spheroid, its polar diameter being about 43 km. (nearly 27 miles) shorter than its equatorial diameter.

2. Why does a 100-pound iron ball fall with no greater acceleration than a 1-pound ball of the same material?
3. If the earth's mass were doubled without any change of volume, how would the change affect weight?
4. How many times must you increase the distance between the centers of gravity of two uniform spheres in order that the gravitation stress between them may become one fourth as great?
5. (a) If a body on the surface of the earth be 4000 miles from the center of the earth, and weigh at this place 100 pounds, what would the same body weigh if it were taken 4000 miles above the earth's surface? (b) What, 2000 miles above the earth? (c) What, 100 miles above the earth?
6. If in Boston $g = 980.4$ cm. at sea level, what is the value of g at a point 5 miles above sea level?
7. What retains the planets in their orbits?
8. If there were but one body of matter in existence, (a) would it have weight? (b) would it have mass?
9. What is the character of the motion produced by a constant force acting on a free body?
10. If the Eskimo children indulge in the sport of coasting, why may their sleds run a little faster than those of the inhabitants of lower latitudes?

SECTION XI

THE PENDULUM

76. Laws of the Pendulum.—A body so supported that it can swing to and fro about a fixed axis under the action of a force is called a *pendulum*.

Experiment 1.—From a bracket suspend by strings leaden balls, as in Fig. 85. Draw B and C to one side, and to different heights, so that B may swing through an arc of, say, 5° , and C through an arc about twice as great, and let both drop at the same instant. C moves faster than B , and completes a longer journey at each swing, but both complete their swing, or vibration, in the same time.

Hence, (1) the vibrations of a pendulum through small arcs are isochronous¹ (*i.e.*, made in equal times) and are independent of the length of the arc.

Experiment 2.—Set all the balls swinging: only *B* and *C* swing together; the shorter the pendulum, the faster it swings. Make *B* 1 m. long and *F* $\frac{1}{4}$ m. long.

With watch in hand, count the vibrations made by *B*. It completes sixty vibrations in about one minute; in other words, it “beats seconds.” A pendulum, therefore, to beat seconds must be 1 m. long (more accurately, in the latitude of Boston at sea level, .9935 m., or 39.117 inches). Count the vibrations of *F*; it makes 120 vibrations in the same time that *B* makes sixty vibrations. Make *G* one ninth the length of *B*: the former makes three vibrations while the latter makes one; consequently the time of vibration of the former is one third that of the latter.

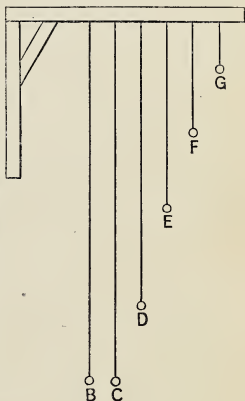


FIG. 85

Hence, (2) the time of vibration of a pendulum varies as the square root of its length, or,

$$t : t' :: \sqrt{l} : \sqrt{l'}.$$

Since the number of vibrations made in a given time varies inversely as the time of one vibration

$$\left(\text{i.e., } n : n' :: \frac{1}{t} : \frac{1}{t'} \right),$$

it follows that (3) the number of vibrations made by a

¹ The isochronism of the pendulum was discovered (1583) by Galileo while watching the swinging of the great lamp suspended in the cathedral at Pisa. In 1641, after he had become blind, he dictated to his son a model of the first pendulum clock.

pendulum in a given time varies inversely as the square root of the length of the pendulum, or,

$$n:n'::\frac{1}{\sqrt{l}}:\frac{1}{\sqrt{l'}}.$$

Since the motion of a pendulum is due to the force of gravity, it follows that where this force is greatest the time of vibration is shortest. Inasmuch as the force of gravity varies with the latitude of the place (§ 75), it follows that the time of vibration of a pendulum at different latitudes varies. By methods too difficult for school purposes it may be shown that (4) the time of vibration of a pendulum varies inversely as the square root of the acceleration (g) produced by gravity, or,

$$t:t'::\frac{1}{\sqrt{g}}:\frac{1}{\sqrt{g'}}, \text{ and } n:n'::\sqrt{g}:\sqrt{g'}.$$

The relation between the acceleration at any locality, the time of vibration of a pendulum, and the length of a pendulum is such that if any two of these quantities be known, the third can be calculated from the following formula¹:

$$t = \pi \sqrt{\frac{l}{g}}; \text{ whence, } g = \frac{\pi^2 l}{t^2}.$$

The determination of the value of g at different parts of the earth is of such great interest in many ways that various governments have employed skilled men to make careful pendulum observations in all accessible regions of the earth.

77. Simple Pendulum ; Center of Oscillation.—A *simple pendulum* is a sizeless mass supported by a weightless thread. Such a pendulum can exist only in the

¹ In this formula t represents the time of a single swing from one extreme position to the other.

imagination, but the conception is useful. Every real pendulum is a *compound pendulum*, which may be supposed to be composed of as many simple pendulums bound together as there are particles in the pendulum.¹ Those particles nearest the point of suspension tend to quicken, and those farthest away tend to check, the motion of the combination. It is apparent that there must be in every compound pendulum a particle so situated that its motion is neither quickened nor checked by the combined action of the particles above and below it. The location of this particle is called the *center of oscillation*. The *real length* of a compound pendulum is the distance of this point from the point of suspension, and it is this length that is referred to in the laws of the pendulum.

Weights (called *bobs*) are usually attached to the lower ends of pendulum rods, which serve to bring the center of oscillation low down in the pendulum and thus lengthen the time of vibration. The time of vibration of a pendulum is shortened or lengthened at will by raising or lowering its bob, which is usually accomplished by turning a thumbscrew just beneath the bob.

EXERCISES

1. In the experiments given above, the arcs of vibration of the pendulums slowly decrease in size. Does this alter the time of vibration?

2. On what two things does the time of vibration of a pendulum depend?

3. Ought the weight of the bob to affect the time of vibration of a pendulum? (See § 70.)

¹ The lighter the threads and the smaller the balls used in the above experiments, the more closely do the pendulums approximate to simple pendulums. It is sufficiently accurate in these experiments to consider the centers of oscillation of the pendulums to be at the centers of the balls.

4. State the chief common use, and the chief scientific use, of a pendulum.

5. (a) What is the length of a pendulum that beats half seconds? (b) quarter seconds? (c) that makes one vibration in 2 seconds? (d) that makes two vibrations per minute?

6. State the proportion that will give the number of vibrations per minute made by a pendulum 40 cm. long.

7. How will the periods of vibration compare in the case of two pendulums the lengths of which are, respectively, 4 feet and 49 feet?

8. Two pendulums make, respectively, fifty and seventy vibrations per minute. Compare their lengths.

9. How long must a pendulum be to make one vibration in 5 seconds in Boston?

10. One pendulum is 20 inches long, and vibrates four times as frequently as another. How long is the other?

11. What effect on the time of vibration of a pendulum has the length of the arc?

12. How can you quicken the vibration of a pendulum threefold?

13. A clock loses time. (a) What change in the pendulum ought to be made? (b) How would you make the correction?

14. Two pendulums are 4 and 9 feet long, respectively. While the short one makes one vibration, how many will the long one make?

15. What is the time of vibration of a pendulum ($39.09 \div 4 =$) 9.77 inches long?

16. If a certain pendulum vibrate once a second, what is the time of vibration of one twenty-five times as long?

17. (a) How will the time of vibration of a pendulum be affected by taking it to the top of a high mountain? (b) by taking it farther from the equator, *i.e.*, to a place of higher latitude?

18. If a clock keep correct time in Chicago, what change in its pendulum must be made that it may keep correct time in New Orleans?

SECTION XII

WORK, ENERGY, AND POWER

78. Work. — When a force causes a change of motion or maintains motion against resistance, it is said to *do work*. A force to do work *must effect a change of position*. *Force and distance* are essential to work. *An unbalanced force always does work*, inasmuch as it always causes a change of motion or overcomes resistance.

The force that moves a body is said to do work upon it, and the body that is moved is said to have work done upon it.

When the heavy weight of a pile driver is raised, work is done upon it; when it descends and drives the pile into the earth, work is done upon the pile, and the pile in turn does work upon the matter in its path.

79. Energy. — The *energy* of a body is its capacity for doing work. The work done by a body, or done upon a body, is a measure of its loss or gain of energy; hence, work and energy are measured in the same units.

The act of doing work consists either in a transfer of energy from the body doing work to the body upon which work is done, or in a transformation of one kind of energy into another kind. For example, when the pile driver strikes the pile and the pile is forced into the earth, a portion of the energy of the pile driver is transferred to the pile, since the pile is made to move; another portion is transformed into *heat* at the point where the blow is delivered. It will be shown in a future chapter that *heat is a form of energy*. *Work*, therefore, may be defined as *the act of transmitting or of transforming energy*.

80. Kinetic and Potential Energy. — Every moving body can do work, because, by virtue of its own momentum it can impart motion to other bodies; hence, *every moving body possesses energy*. The energy which a body possesses in consequence of its motion is called *kinetic energy*.

A body at rest also possesses energy whenever its *position* or *condition* is such that it can move and will move if allowed to do so. For example, a stone raised above the earth and resting on a shelf is capable of motion and ready to move and to do work when the shelf shall be removed.

Every youth knows that when he is on a bicycle at the top of a hill he possesses energy that will carry him to the foot of the hill without pedaling. A “head” of water is something other than water; it is something associated with matter in virtue of its elevation. The energy of all bodies consists either in their motion or in their capacity to move. Energy due to capacity to move is called *potential energy*. It is the capacity for doing work which a body has *in virtue of the fact that its position is such that it is possible for it to move, and in virtue of the existence of a stress that tends to move it.*

A body possessing potential energy is often spoken of as a body having energy *stored* in it. Examples: A watch spring and the weights of a clock when wound up have energy stored in them which is doled out gradually in moving machinery. We store energy when we bend a bow, condense air, raise a hammer, and stretch a piece of rubber or an elastic spiral wire. When a body, *e.g.*, a stone, is projected vertically upward, its kinetic energy is rapidly expended in raising the stone against the force of gravity, and entirely disappears when the body reaches its highest point;

but the energy is by no means lost. It has simply been converted into the potential state; in other words, it has been stored. It reappears as kinetic energy during the fall of the body. Show that in every swing of a pendulum there are two similar transformations of energy.

It is important to observe that a body acquires energy, either kinetic or potential, *only at the expense of work*.

81. Potential Energy of Chemical Separation.—Matter may possess potential energy in virtue of chemical separation against a force called *chemical affinity*, and the potential energy is a measure of the work done in effecting the separation. For example, the entire value of coal consists in its potential energy, which was stored by the work performed through the agency of the sun's energy in separating the carbon of carbon dioxide from the oxygen. Gunpowder possesses potential energy sufficient to do a quantity of work, *e.g.*, in blasting, that would occupy many laborers a long time.

The foregoing discussions lead to the following conclusion: *a body possesses potential energy when, in virtue of work done upon it, it occupies a position, or its constituent particles occupy positions, such that the energy expended can be restored at any time by the return of the body to its original position, or by the return of its particles to their original positions.*

82. Units of Work and Energy.—The unit adopted for measuring work and energy is *the work done, or energy imparted, when the force of 1 kg. acts through the distance of 1 m.* It is called a *kilogrammeter*. The British unit is the work done when the force of 1 pound acts through the distance of 1 foot, and is called a

foot-pound. The kilogrammeter (kgm.) is equivalent to 7.233 foot-pounds.

83. Formulas for calculating Work or Energy.— Force and distance, being the only elements of work, are necessarily the quantities employed in calculating work. A given force acting through a distance of 1 m. does a certain quantity of work; it is evident that the same force acting through a distance of 2 m. would do twice as much work. Hence, the general formula:

$$(1) w = fs,$$

in which f is the force employed, s the distance through which the force acts, and w the work done.

Often the work done upon a body is more conveniently determined by *multiplying the resistance by the space through which it is overcome*, and our formula becomes, by substitution of r (resistance) for f (the force which overcomes it),

$$(2) w = rs.$$

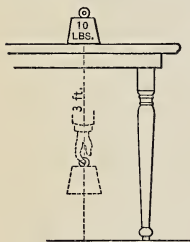


FIG. 86

Fig. 86 is a pictorial illustration of the work performed upon a weight by the muscular force exerted by the arm against the downward force of gravity in raising the weight to the top of a table. When

the weight reaches the top of the table how much energy is stored in it?

84. Absolute Units of Work and Energy.— If, in calculating work by the formula $w = fs$, the force (f) be expressed in grams, and the distance (s) through which it acts be expressed in centimeters, the work (w) will be

expressed in a very small gravitation unit called a *gram-centimeter*. But if force be measured in dynes and distance in centimeters, the work done is expressed in an absolute unit which might properly be called a dyne-centimeter, but which is usually called an *erg*.

An erg is the work done or energy imparted by a force of 1 dyne acting through a distance of 1 cm.

Now, since 1 gram-force is equivalent to g dynes (§ 69), it is evident that 1 gram-centimeter is equivalent to g ergs.

The following list of equivalents will be of service in changing gravitation units to absolute units, and *vice versa*:

1 kilogrammeter \approx 100,000 gram-centimeters.

1 kilogrammeter \approx 100,000 g ergs.

1 gram-centimeter \approx g ergs.

85. Formulas for calculating the Kinetic Energy of a Body when its Mass and its Velocity are known. — Suppose a body having a mass, m , to be moving with a velocity, v ; its kinetic energy can do a definite quantity of work before the body comes to rest. Suppose it to be moving vertically upward, its kinetic energy expending itself in raising the body. If its velocity be such that it will rise to a height, s , then its energy at the start is just sufficient to do ($f = ma$ or mg , § 69) mgs absolute units of work, or

$$(1) E_k (\text{kinetic energy}) = mgs.$$

We may find, then, to what height, s , a body having a velocity, v , would rise if directed vertically upward, and

from formula (1) determine its kinetic energy. Substituting g for a in formulas (2) and (3), § 44, and eliminating t , we find $s = \frac{v^2}{2g}$. Substituting this value for s in formula (1), we have

$$(2) E_k = \frac{mv^2}{2},$$

a formula which will determine the kinetic energy of a body in *ergs* when its mass, m , is expressed in grams, and its velocity, v , is expressed in centimeters per second, since the kinetic energy of a body is the same whatever be the direction of the motion.

Hence, the kinetic energy of a body, expressed in absolute units, is half the product of its mass multiplied by the square of its velocity.

If the result be desired in gravitational units, for example, in gram-centimeters, the number of absolute units must be divided by g , since g ergs (980) are equivalent to 1 gram-centimeter.¹

Accordingly, the formula (3) $E_k = \frac{mv^2}{2g}$ will determine the kinetic energy of a body in the gravitational units, gram-centimeters, kilogrammeters, or foot-pounds, according as its mass, m , is expressed in grams, kilograms, or pounds, and its velocity, v , is expressed in centimeters per second, meters per second, or feet per second, and the corresponding numerical value of g be taken as 980, 9.8, or 32.2, respectively.

¹ For convenience in the solution of problems we adopt 980 for the value of g . Strictly, the value of g at sea level in latitude 45° (see § 15) is 980.6.

EXERCISES

1. Do the stones in the Egyptian pyramids still retain the energy that was expended in raising them to their places?

2. The potential energy of a stone raised above the earth is represented by the expression mgs (§ 85); on what three things then does it depend?

3. What quantity of energy will a force of 10 pounds impart to a body in acting on it through a space of 65 feet, if none be lost or wasted?

4. How much work is done in raising 12 cubic feet of water 20 feet?

5. How many kilogrammeters of potential energy does a mass of 800 dm.³ of water possess when elevated 40 m. above the earth?

6. (a) Suppose that an average force of 25 pounds is exerted through a space of 10 inches in bending a bow, what amount of energy will it give the bow? (b) What kind of energy will the bow, when bent, possess?

7. (a) What quantity of energy must be imparted to a bullet whose mass is 1 ounce ($\frac{1}{16}$ pound) that it may rise 257.6 feet? (b) What change in its energy is going on while it rises? (c) When it falls to the earth what change in its energy occurs?

8. What amount of work is done by a man in sawing through a stick of wood, if he causes the saw to move 10 m. against an average resistance of 5 kg.?

9. Why can you throw a stone farther than you can throw a cork?

10. (a) How many foot-pounds of kinetic energy does a mass of 20 pounds, moving with a velocity of 50 feet per second, possess? (b) How much work can it do?

11. (a) Refer to formulas (2) and (3), § 85, and state how many times the kinetic energy of a body is increased by doubling its velocity. (b) The kinetic energy of a body of a given mass is proportional to what?

12. A force of 450 pounds acts upon a body through a space of 80 feet. One fourth of the work is wasted in consequence of resistances. How much available energy is imparted to the body?

13. A horse draws a carriage on a level road at the uniform rate of 5 miles an hour. (a) Does the energy of the carriage accumulate?

(b) What kind of energy does the carriage possess? (c) Suppose that the carriage were drawn up a hill, would its energy accumulate? (d) What kind of energy would it possess when at rest on the top of the hill? (e) How would you calculate the quantity of energy it possesses when at rest on top of the hill? (f) Suppose that the carriage is in motion on top of the hill, what two formulas would you employ in calculating the total energy which it possesses?

14. How many kilogrammeters of kinetic energy does a body of mass 500 grams acquire in falling freely 5 seconds?

15. How many gram-centimeters are stored in a watch spring if an average force of 25 g. acts through a distance of 20 cm. while winding it?

16. How many ergs of work are done in raising 2 kg. of matter 1 m. high where $g = 980$?

17. A certain body has 600 ergs of kinetic energy. How far will this energy carry the body against a constant resistance of 20 dynes?

18. (a) A body whose mass is 20 g. moves with a velocity of 12 m. per second. How many ergs of kinetic energy has it? (b) Would the answer be the same if the body were 4000 miles above the earth?

19. (a) Show that momentum is a *time* effect of a force, and that energy is a *distance* effect of a force. (See §§ 66 and 85.)

20. A constant force of 20 dynes moves a body 100 cm. What amount of work is done?

21. If the steam be shut off, whence comes the energy that keeps the train in motion for a time?

86. Power. — In estimating simply the total quantity of work done, the time consumed is not considered. The work done by a hod carrier, in carrying 1000 bricks to the top of a building, is the same whether he does it in a day or a week. But in estimating the *rate* at which an agent is capable of doing work, time is an important element. The *power* of an agent, *e.g.*, of a steam engine, of an animal, of a stream of water, is the *rate* at which it does or can do work, and is measured by the quantity

of work it does *per unit of time*, and is determined by the formula

$$P \text{ (power)} = \frac{w \text{ (work)}}{t \text{ (time)}}.$$

The work done by a horse in raising a barrel of flour 20 feet is about 4000 foot-pounds; even a mouse could do the same quantity of work in time, but he has not the power of a horse.

Power is calculated in a unit called a *horse-power*. A horse-power is the capacity of doing 550 foot-pounds per second, or 33,000 foot-pounds per minute. The objective existence of power is curiously recognized in advertisements that we frequently see, such as "Spare power to let," etc.

EXERCISES

1. For which is a truck horse valued, his energy or his power?
2. Do we speak of the power or the energy of the steam engine?
3. Shall we say that the power, or the energy, of the horse is greater than that of man?
4. How much work can a 2 horse-power engine do in an hour?
5. (a) What quantity of work is required to raise 50 tons of coal from a mine 200 feet deep? (b) An engine of how many horse-power would be required in order to do it in 2 hours?
6. A car of 3 tons mass is drawn by a horse at a speed of 180 feet per minute. The index of the dynamo meter to which the horse is attached stands at 800 pounds. (a) At what rate is the horse working? (b) Express the rate in horse-power.
7. A dynamometer shows that a span of horses pulls a plow with a constant force of 1500 pounds. What power is required to work the plow if they travel at the rate of 2 miles per hour?
8. What is the horse-power of an engine that will raise 1,350,000 pounds 50 feet in an hour?
9. How long will it take a 3 horse-power engine to raise 10 tons 50 feet?

10. How far will a 2 horse-power engine raise 3000 pounds in 10 seconds?

11. The wind moves a vessel with a uniform velocity of 5 miles an hour against a constant resistance of 2000 pounds. What power is furnished by the wind?

12. If a 2 horse-power engine can just throw 1056 pounds of water to the top of a steeple in 2 minutes, what is the height of the steeple? (Disregard the resistance of the air.)

13. Supply the following ellipses by selecting appropriate words from the following: *viz.*, force, work, energy, power. When — acts through space — is performed, and — is imparted. The rate at which — is performed determines the — of the agent. The — of a bullet flying through vacant space. The — of a horse. The — of wind. The — of a bent bow. What — must a bullet of mass 1 ounce have that it may rise 4 seconds? What — is consumed by a steamer in crossing the ocean? What — is necessary that it may traverse 300 knots per day, and what must be the average — exerted to overcome the resistances at the required rate?

14. It is estimated that 300,000 cubic feet of water plunge over the Niagara escarpment 150 feet downward every second. What power does this represent?

15. (a) A bicycle rider moves up a grade against the wind. Against what forces does he work? (b) From which expenditure of energy can he get a return, and how?

16. A stone of volume 10^3 cc., specific gravity 2.6, is raised from the bottom of a lake to the surface, a distance of 20 m. Find the work done in kilogrammeters. *Ans.* 32 kgm.

SECTION XIII

MACHINES

87. **Universal Law of Machines.**—Machines are instruments used to *transmit* or to *transform* work or energy. At present we deal with machines employed as means for transmitting and modifying motion and force. In

future chapters we shall consider machines whose function is to transform energy, such as the steam engine, dynamo, etc.

Figs. 87, 88, and 89 represent machines in very common use, called, respectively, the *pulley*, the *lever*, and

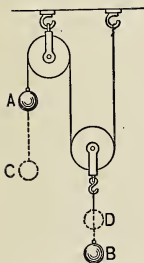


FIG. 87

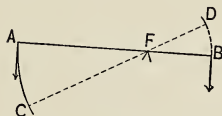


FIG. 88

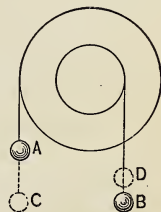


FIG. 89

the *wheel and axle*. Let A be the point of application of the force which does work upon the machine in each case and B be the point where the machine does work upon some body that is to be moved, or exerts force against some resistance to be overcome. Let f represent the force¹ applied to the machine, and r the resistance overcome. Let s represent the distance AC through which the force acts, and s' the distance BD through which the resistance is moved. Then fs will represent (§ 83) the work done upon the machine, or

¹ In the discussion of machines it is quite customary to call the force applied to a machine *power*, and the resistance overcome *weight*. While this nomenclature appears to have nothing to recommend it save custom, there are obvious disadvantages arising from ambiguity in the use of these terms.

the *applied work*, and rs' the work done upon the resistance, or the *transmitted work*.

If no work were lost or wasted in consequence of friction or other resistances, in every machine the applied work and the transmitted work would be equal, *i.e.*, $fs = rs'$. But, since in all machines some work is wasted in practice, rs' is always less than fs , so that our formula becomes

$$fs = rs' + w,$$

in which w represents the waste work. We infer from this that no machine *creates* or *increases* energy, — rather, every machine is a *waster* of energy. We also infer that a perpetual-motion machine is an impossibility.¹

Recurring to the three figures above, we see that in each case the distance AC (or s), through which the force acts, is greater than the distance BD (or s'), through which the resistance is overcome. Consequently, since fs and rs' are equal,² f may be made as many times smaller than r as s is larger than s' . Hence, the Universal Law of Machines:

The force and the resistance vary inversely as the distances through which their respective points of application move, or,

$$f:r = \frac{1}{s}:\frac{1}{s'}.$$

It thus appears that machines may enable us to overcome large resistances with conveniently small forces by

¹ It is interesting to note that the French Academy, as early as 1775, declined to consider any further devices for securing "the perpetual motion," that is, machines which should not only keep running for an indefinite time, but also perform useful work (Hastings and Beach).

² All calculations are based upon the supposition that machines are perfect, that is, do not waste energy.

making the ratio $s:s'$ correspondingly large. The ratio $r:f (= s:s')$ is called the *ratio of gain of force*.

If the points of application of the force and of the resistance in the machines described above be interchanged, so that DB is the distance (s) through which the force acts, and CA is the distance (s') through which the resistance moves, f must be larger than r in proportion as s' is larger than s . In this case speed is gained at the expense of force. This gives rise to the common expression, *what is gained in speed is lost in force*, and *vice versa*. A gain of force or a gain of speed is called a *mechanical advantage*.

88. Special Laws of Machines. — While the general law of machines (§ 87) is always applicable, its application is not always convenient, since, for example, it necessitates putting the machine in motion in order to measure s and s' (the distances traversed, respectively, by the points of application of the force and resistance in the same time), an operation which would be very difficult and tedious in many cases. Hence, a *special law*, one in which the equality between the ratio of gain and the ratio between certain dimensions of the machine is stated, is often more convenient in practice.

For example, in case of the lever (Fig. 88), force and resistance vary inversely as their respective leverages,¹ or,

$$f:r = \frac{1}{l} : \frac{1}{l'},$$

¹ The pupil will not fail to observe that in ascertaining the relations between the force and the resistance when applied to the lever and to the wheel and axle he is dealing with *moments* around the axis of rotation.

in which l and l' represent, respectively, the leverage of the force and that of the resistance.

Again, in case of the wheel and axle (Fig. 89),

$$f : r = \frac{1}{d} : \frac{1}{d'},$$

in which d represents the diameter of the wheel and d' the diameter of the axle.

89. Uses of Machines classified. — The various uses of machines may generally be classified under the following heads:

1. *They may enable us to exchange intensity of force for speed, or speed for intensity of force.*

2. *They may enable us to employ a force in a direction that is more convenient than the direction in which the resistance is to be moved, e.g., fixed pulleys, as shown at A and B in Fig. 90.*

3. *They may enable us to employ other forces than our own muscular force in doing work, e.g., the muscular force of animals (Fig. 90), the forces of wind, water, steam, etc.*

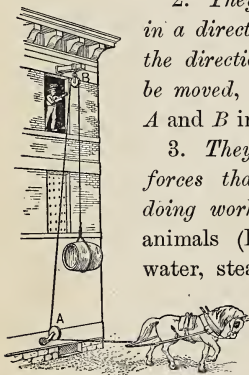


FIG. 90

90. Efficiency of Machines.

— The *efficiency* of a machine is a fraction, usually stated as a *per cent*, which expresses the ratio of the energy given

out by the machine and utilized, to the total energy expended upon the machine. The limit of the efficiency of a machine is *unity*, or 100 per cent, which is the

efficiency of an "ideal" machine, in which no energy is lost. The object of improvements in machines is to bring their efficiency as near to unity as possible.

For instance, if of 50 foot-pounds of energy expended on a machine, 8 foot-pounds be converted by friction into heat, and 5 foot-pounds be lost in consequence of the utilization of only a component of the working force, so that the machine is able to give out only 37 foot-pounds, its efficiency is $\frac{37}{50} = 74$ per cent. If the friction can be reduced one half, and an improvement can be made in the machine that will render the entire working force effective, then there will be wasted only 4 foot-pounds of energy, its efficiency will be raised to $\frac{46}{50} = 92$ per cent, and the quantity of work which the machine will accomplish will be increased in the ratio of 92 : 74.

EXERCISES

1. (a) When is force said to be gained by the use of a machine ?
(b) When is speed said to be gained ?

2. State how you would use a lever in order to gain force in the ratio of 7 : 2.

3. (a) On what condition will speed be multiplied by a wheel and axle in the ratio of 5 : 2 ? (b) Where must the force and resistance be applied in this case ?

4. (a) With which of the two pulleys, *i.e.*, the fixed or the movable pulley, is mechanical advantage gained ? (b) What purpose does the other pulley serve ?

5. (a) Where is the fulcrum or axis of motion in a claw hammer (Fig. 91) ?

(b) If the distance from the fulcrum to the center of the hand be 15 inches, the distance of the nail from the fulcrum be 3 inches, and



FIG. 91

the resistance offered by the nail be 80 pounds, what force must be exerted by the hand to start the nail?

6. (a) What advantage is gained by a nutcracker (Fig. 92)?
(b) What is the ratio of gain?



FIG. 92

7. Energy is applied to a machine at the rate of 250 foot-pounds per minute, and it transmits 200 foot-pounds per minute. What is its efficiency?

8. (a) What advantage is gained by cutting far back on the blades of shears near the fulcrum (Fig. 93)? Why? (b) Should shears for cutting metals be made with short handles and long blades, or the reverse? (c) What is the advantage of long blades?



FIG. 93

9. The arm is raised

by the contraction of the muscle *A* (Fig. 94), which is attached at one extremity to the shoulder and at the other extremity, *B*, to the forearm, near the elbow. (a) When the arm is used, as represented

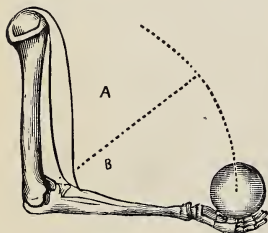


FIG. 94

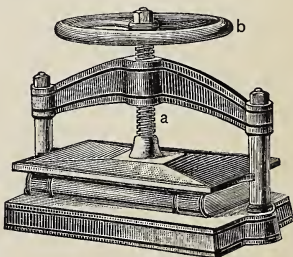


FIG. 95

in the figure, to raise a weight, what kind of a machine is it? (b) What mechanical advantage is gained by it? (c) The ratio of gain is the ratio of what to what?

10. What must be the ratio of the diameter of a wheel to the diameter of its axle that 50 pounds may support 1 ton (2000 pounds)?

11. Suppose the screw in the letter-press (Fig. 95) to advance $\frac{1}{4}$ inch at each revolution, and a force of 25 pounds to be applied to the circumference of the wheel *b*, whose diameter is 14 inches; what pressure would be exerted on articles placed beneath the screw?

12. Two weights, of 5 kg. and of 20 kg., are suspended from the ends of a lever 70 cm. long. (a) Where, disregarding the weight of the lever, must the fulcrum be placed that they may balance? (b) What will be the pressure on the prop?

13. (a) The pistons of a hydraulic press (§ 18) are, respectively, 2 inches and 12 inches in diameter. What is the ratio of gain of force obtained by the transmission of fluid pressure? (b) Suppose that a force of 20 pounds be applied to the long arm of a lever whose arms are as 15:3, and this force causes the short arm to produce a downward pressure on the small piston, what will be the total upward pressure exerted by the large piston?

14. How great a force will be required to support a ball weighing a ton on an inclined plane whose length is twenty times its height? (See § 63.)

15. Show why it is easier to draw a load up an inclined plane than to lift it vertically.

16. If the circumference of an axle (Fig. 96) be 60 cm., and the point of application of the force applied to the crank travel 240 cm. during each revolution, what force will be necessary to raise a bucket of coal weighing 40 kg.?

17. Through how many meters must the force act to raise the bucket from a cavity 10 m. deep?

18. (a) A skid 12 feet long rests with one end on a cart at a height of 3 feet from the ground. What force will roll a barrel of flour weighing 200 pounds over the skid into the cart? (b) What amount of work will be required? (c) What amount of work will be required if the barrel is raised without the use of the skid?

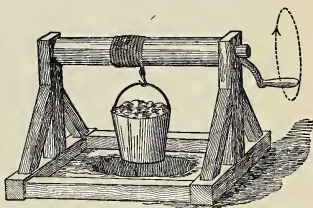


FIG. 96

SECTION XIV

SOME PROPERTIES OF MATTER DUE TO MOLECULAR FORCES

91. Cohesion, Tenacity, and Rigidity. — In solids and liquids the molecules are held together by an attractive force, called *cohesion*, which prevents their separation except under the action of considerable external force. This is the force which resists an effort tending to break, tear, or crush a body. The *tenacity* or *tensile strength* of solids and liquids, *i.e.*, the resistance which they offer to being pulled apart, is due to this force. It is usually greater in solids than in liquids, and is entirely wanting in gases.

Cohesion tends to hold the molecules of a solid in fixed relative positions, thus giving the solid a definite shape. It gives to a solid *rigidity*, or ability to resist a change of shape. Different solids possess very different degrees of rigidity.

92. Cohesion in Liquids. — Clean glass is wet by water. If a glass plate be dipped into water and then withdrawn, a layer of water clings to the glass. When the glass is withdrawn water is torn from water, and not glass from water. This shows that the attraction of the molecules of water for one another is weaker than the attraction between glass and water. Or if, to save words, we call the attraction between the solid and the liquid *adhesion*, then we may say that the *cohesion* between the molecules of the water is weaker than the *adhesion* between the glass and the water.

Clean glass is not wet by clean mercury, which shows that the adhesion between glass and mercury is not so great as the cohesion in mercury. Generally speaking, a solid is wet by a liquid when the adhesion of the solid to the liquid is greater than the cohesion of the liquid, and is not wet when the cohesion is greater than the adhesion.

93. Elasticity and Plasticity.—*Elasticity* is that property in virtue of which a solid tends to recover its size or shape, and a fluid its size, after these have been changed by external force. If the body recover at once and completely on the removal of the stress, the body is said to be *perfectly elastic*. All fluids are perfectly elastic, and a few solids are approximately so, such as ivory and glass.

If a solid have little or no tendency to recover its size and shape after distortion, it is said to be *plastic* or *inelastic*. Such substances are putty, wet clay, and dough. A great number of substances are elastic when the distorting forces are small, but break or receive a "set" when these forces are too great. They are said to be elastic "within certain limits," called the *limits of elasticity*. If strained beyond those limits, they become more or less plastic. The springs of a buggy sometimes become set from bearing a too heavy load and lose permanently much of their elasticity, that is, they become in a degree plastic.

94. Malleability and Ductility.—Solids which possess that kind of plasticity which renders them susceptible of being rolled or hammered out into sheets are said to

be *malleable*. Most metals are highly malleable. Gold may be hammered so thin as to be transparent, or to a thickness of $\frac{1}{300000}$ of an inch. Most substances that are malleable are also susceptible of being drawn out into fine threads, *e.g.*, wires of different metals. Such substances are said to be *ductile*. Platinum has been drawn into wire 0.000165 inch thick, or so fine as to be scarcely visible to the unaided eye.

Wires are made by drawing a rod of metal in succession through a number of holes, each a little smaller than the last, the diameter of the rod continually decreasing while its length is correspondingly increased.

95. Surface Tension. — When a piece of sheet rubber is stretched there exists between its molecules a contractile stress, called *tension*, which tends to restore the body to its normal condition. Every liquid behaves *as if* a thin film forming its external layer were ever in a state of tension, or were exerting a constant effort to contract. This superficial film is tough or hard to break as compared with the interior mass. If a needle be carefully laid on the surface of still water, it will float, although the density of steel is more than seven times that of water. The tendency of a liquid surface to contract means that it acts like an elastic membrane, equally stretched in all directions, and by a constant tension.

Experiment. — Form a soap bubble at the orifice of the bowl of a tobacco pipe, and, removing the mouth from the pipe, observe that the tension of the two surfaces (exterior and interior) of the bubble drives out the air from the interior until finally the bubble contracts to a flat sheet.

As a consequence of surface tension, *every body of liquid tends to assume the spherical form*, since the sphere has less surface than any other form having equal volume. The water remaining on the end of a glass rod that has been dipped in water is globular, as if a rubber bag filled with water were tied about the rod. In bodies of large mass the distorting forces due to their weight are generally sufficient to disguise the effect; but in bodies of small mass, *e.g.*, drops of liquids and soap bubbles, it is apparent. The hairs of a camel's-hair brush when dry present a bushy appearance. When dipped into water the same appearance remains, but when taken out of water the surface tension of the adhering film of water draws the hairs closely together.

96. Capillary Phenomena. — If glass tubes (Fig. 97) of capillary (hairlike) bore be thrust into water, the water will rise in the bores considerably above the general level outside. If similar tubes (Fig. 98) be thrust

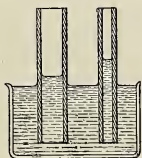


FIG. 97

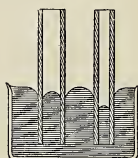


FIG. 98

into mercury, the mercury within the bores will be depressed below the surface outside. Phenomena of this kind are called *capillary phenomena*. The free surfaces of the liquids inside the bores are curved, the surface of water being concave and that of mercury convex. The size of the bores of the tubes is greatly exaggerated in the two figures in order to show this more plainly. The smaller the bore of the tube, the greater is the elevation or depression of the liquid.

The phenomena of capillary action are well shown by placing various liquids in U-shaped glass tubes having one arm reduced to a capillary size, as *A* and *B* in Fig. 99. Mercury poured into *A*

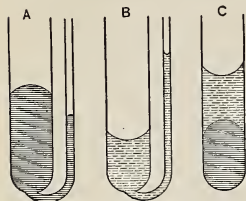


FIG. 99

FIG. 100

assumes convex surfaces in both arms, but does not rise as high in the small arm as it does in the large arm. Pour water into *B*, and all the phenomena are reversed. Fig. 100 shows the forms that the surfaces of water and mercury take when contained in the same glass tube.

The following are the laws of capillary action :

I. Liquids rise in tubes when they wet them, and are depressed when they do not.

II. The elevation or depression varies inversely as the diameter of the bore.

III. The elevation or depression depends also upon the three substances involved in the experiment, that is, on the substance of the tube, on the liquid, and on the substance that fills the space above the surface of the liquid.

CHAPTER IV

HEAT

SECTION I

KINETIC THEORY OF HEAT — SOURCES OF HEAT

97. *Heat defined.* — As was stated in § 3, the molecules of every body are believed to be in incessant motion. If this be true, it follows that all molecules must possess kinetic energy. The name given to this particular type of energy is *heat*. It is certain that *heat is a form of energy*, and no one at the present day doubts that it is *due to the motion of the molecules of a body*. The conclusion is that *heat is molecular kinetic energy*. Like the form of energy already treated, it involves the two elements, *matter and motion*.¹

According to this view, a body becomes warmer as the motion of its molecules is quickened and cooler as the motion of its molecules is retarded. The coldest bodies we know have heat, since no molecules are ever at rest. We think of ice as being very cold, and the erroneous impression exists to some extent that ice is heatless matter, but the fact is that no one ever found ice so cold that it could not become colder. In other words, the motions of the molecules of the coldest ice in the Arctic regions may become less rapid. The expression "as cold as ice" is wholly vague.

¹ As late as the beginning of the nineteenth century heat was generally regarded as an "igneous fluid," sometimes called "caloric." Experiments performed by Count Rumford, Joule, and others have demonstrated the falsity of this view and have led to the adoption of the *kinetic theory*.

The term *heat* is used in two very different senses, the *physical* and the *physiological*. In physics we deal with heat only as molecular kinetic energy. In a physiological sense, heat is considered as a *sensation* which we experience by contact with bodies. Thus, we declare bodies to be *cold*, *warm*, or *hot*, according to the sensations which we experience when we come in contact with them. Our sensations, however, are very unreliable criterions in judging of the relative heat conditions of different bodies, for the sensations produced depend on many other things besides the degree of heat in the body touched.

98. Molar Energy Convertible into Heat.—If you hammer a nail briskly, it soon becomes too hot to be handled with comfort. Sticks of wood may become so heated by being rubbed together as to take fire. When a hammer strikes an anvil its motion as a mass ceases; but the hammer and anvil are heated, that is, the motions of the molecules of the hammer and anvil are quickened. There is no destruction of motion, — *only a change from mass motion to molecular motion*, or, in other words, *a change from molar or mass energy to molecular energy*, i.e., *heat*.

Another interesting illustration of the generation of heat by the expenditure of molar energy is afforded in the case of compression of air. A few drops of carbon disulphide are dropped into the glass barrel *A* (Fig. 101) of a fire syringe, and the tightly fitting piston *B* is suddenly pushed into the barrel. The air in front of the piston is rapidly condensed and becomes so heated as to ignite the chemical and produce a flash of light.

Mass motion checked usually results in heat. When the brakes are applied to the wheels on a moving railroad train its

molar energy is converted into heat, and the wheels, brake blocks, and rails are heated thereby. By friction, by percussion, or by any process by which mass motion is arrested, heat is generated. Saws and augers when used become heated. Meteorites, often called "falling stars," are rendered visible by their intense heat. They are pieces of planetary stone which plunge with prodigious speed into the earth's atmosphere, and their mass motions, being impeded by the friction of the air, produce the heat with which they glow. Sparks are seen at night when the iron shoes of horses strike the stone pavements. A flash of light is seen when a cannon ball strikes an iron-clad vessel or a target.

99. Other Sources of Heat. — Since heat is energy, it may originate in some other form of energy, *i.e., by the transformation of some other form of energy into heat.* In the electric lamp electric energy is transformed into heat. In the combustion of the various fuels, such as wood, coal, oils, and illuminating gas, chemical potential energy is transformed into heat. And, generally, whenever heat is generated by chemical action, as for example when sulphuric acid is poured into water, or water upon quicklime, chemical potential energy is transformed into heat.

Not only is the sun the supreme source of heat, but it is also the source, directly or indirectly, of very nearly all the energy employed by man in doing work. A form of energy called *radiant energy* is continually sent forth from the sun in all directions; the mode of transmission and of its conversion into heat is considered in Chapter VI.



FIG. 101

EXERCISES

1. What is the cause of a "hot box" on a railway car?
2. What does coal possess that gives it value?
3. What evidence have you discovered that heat is a kind of energy and not a kind of fluid?
4. What, only, can be transformed into heat?
5. Are the terms *heat* and *cold* names of things essentially different, or of different degrees of the same thing?

SECTION II

TEMPERATURE AND THERMOMETRY

100. Temperature defined.—When the quantity of heat in a body increases, that is, when the motion of its molecules is quickened, the *temperature* of the body is said to *rise*; and when it diminishes, the temperature is said to *fall*. If body *A* tends to impart heat to body *B*, then *A* is said to have a higher temperature than *B*. Temperature is a *condition* of a body which determines its ability to part with heat to surrounding bodies or to receive it from them. The direction of the flow of heat determines which of two bodies has the higher temperature. If the temperature of neither body rises at the expense of the other, then both have the same temperature and are said to be in *thermal equilibrium*. *The temperature of a body is directly proportional to the average of the squares of the velocities of its molecules.*

101. Construction of a Thermometer.—A *thermometer* is an instrument for indicating temperature. It consists

of a glass tube of uniform capillary bore, terminating at one end in a bulb, the bulb and a part of the tube being filled with mercury, and the space in the tube above the mercury being a partial vacuum. On the tube, or on a plate of metal behind the tube, is a scale to show the height of the mercurial column.

If a thermometer be brought into intimate contact with a body whose temperature is sought, as, for instance, a liquid into which it is plunged, or the air in a room, the mercury in the tube rises or falls¹ until it reaches a certain point, at which it remains stationary. We then know that the mercury has the same temperature as has the surrounding body. Hence, the *reading*, as it is called, of the thermometer indicates the temperature not only of the mercury, but also of the surrounding body.

102. Graduation of Thermometers. — The graduation of a thermometer is based on the fact that the temperature at which ice melts and that at which water boils under a definite pressure being unchangeable, the difference between these two temperatures is constant. The bulb is first placed in melting ice and allowed to stand until the surface of the mercury becomes stationary, when a mark is made at that point which indicates the *melting point*.

Afterwards both bulb and stem are enveloped in steam at a pressure of 760 mm. The mercury rises in the stem until its temperature reaches that of the steam, when it becomes stationary; then another mark is made to indicate the *boiling point*. Then the space between the two points found is divided into a convenient number of equal parts called *degrees*, and the scale is extended above and below these points as far as is desirable.

¹ The thermometer primarily indicates changes of volume; but as changes of volume in this case are caused by changes of temperature, it is commonly used for the more important purpose of indicating *temperature*.

Two methods of division are adopted in this country (see *a* and *b*, Fig. 102): by one, the space is divided into 180 equal parts,

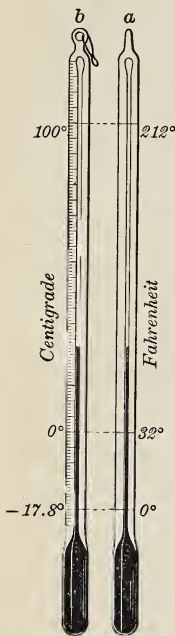


FIG. 102

and the result is called the *Fahrenheit* scale, from the name of its inventor; by the other, the space is divided into 100 equal parts, and the resulting scale is called *centigrade*, which means *one hundred steps*. In the Fahrenheit scale, which is generally employed in the United States for ordinary household purposes, the melting and boiling points are marked, respectively, 32° and 212° . The centigrade scale, which is generally employed by scientists, has its melting and boiling points more conveniently marked, respectively, 0° and 100° . A temperature below 0° in either scale is indicated by a minus sign before the number. Thus, -12° F. indicates 12° below 0° (or 44° below the melting point of ice), according to the Fahrenheit scale. The Fahrenheit and centigrade scales agree at -40° , but diverge both ways from this point.

103. Conversion from One Scale to the Other. — Since 100° C. \approx 180° F., 5° C. \approx 9° F., or 1° C. \approx $\frac{9}{5}$ of 1° F. Hence, to convert centigrade degrees into Fahrenheit degrees, we multiply the number by $\frac{9}{5}$; and to convert

Fahrenheit degrees into centigrade degrees, we multiply by $\frac{5}{9}$.

Now since 0° C. \approx 32° F., if we deduct 32° from the Fahrenheit reading we have the number of degrees by which the given temperature differs from the temperature of melting ice. For example, 52° on a Fahrenheit

scale is not 52° above melting point, but $(52^{\circ} - 32^{\circ} =) 20^{\circ}$ above it.

To reduce a Fahrenheit reading to a centigrade reading, *first subtract 32 from the given number, and then multiply by $\frac{5}{9}$* . Thus,

$$\frac{5}{9} (F. - 32) = C.$$

To change a centigrade reading to a Fahrenheit reading, *first multiply the given number by $\frac{9}{5}$, and then add 32*. Thus,

$$\frac{9}{5} C. + 32 = F.$$

EXERCISES

1. Express the following temperatures of the centigrade scale in the Fahrenheit scale: 100° ; 40° ; 56° ; 60° ; 0° ; -20° ; -40° ; 80° ; 150° .

NOTE. — The 32° should be added or subtracted *algebraically*. Thus, to change -14° C. to its equivalent in the Fahrenheit scale: $\frac{9}{5} \times (-14) = -25.2^{\circ}$; $-25.2^{\circ} + 32^{\circ} = 6.8^{\circ}$, the required temperature in the Fahrenheit scale. Again, to find the equivalent of 24° F. in the centigrade scale: $24 - 32 = -8$; $-8 \times \frac{5}{9} = -4\frac{4}{9}$; hence, 24° F. is equivalent to $-4.4^{\circ} + C$.

2. Express the following temperatures of the Fahrenheit scale in the centigrade scale: 212° ; 32° ; 90° ; 77° ; 20° ; 10° ; -10° ; -20° ; -40° ; 40° ; 59° ; 329° .

3. Explain the origin of the heat obtained by burning coal.

4. How does all heat originate?

5. What must be the temperature of the air that both the centigrade and Fahrenheit thermometers shall read the same?

6. The difference in temperature of two liquids is 36 Fahrenheit degrees; what is the difference in centigrade degrees?

7. (a) If the temperature of the air falls from 20° C. to -8° C., through how many degrees does the temperature drop? (b) through how many Fahrenheit degrees does the temperature drop?

SECTION III

CALORIMETRY

104. Distinction between the Questions "How Hot?" and "How much Heat?" — The former, like the question "How sweet?" when applied to a solution of sugar, is answered only relatively. The latter, like the question "How much sugar in the solution?" is answered quantitatively. Sweetness and temperature are independent of the mass of the body. A pint of boiling water is as hot as a gallon of the same; but the latter contains eight times as much heat. *Temperature depends on the average kinetic energy of the molecules. Quantity of heat is the product of the average kinetic energy of the molecules multiplied by the number of molecules.* The quantity of heat a body has depends, therefore, upon both its *mass* and its *temperature*.

105. Thermal Units. — The unit used for measuring quantity of heat, called a *calorie*, is the quantity of heat required to raise the temperature of 1 kg. of water 1 centigrade degree. The thermal unit in the C.G.S. system is the *gram-calorie*, sometimes called the *smaller calorie*, which is the quantity of heat required to raise 1 g. of water from 4° to 5° C. The operation of measuring heat is called *calorimetry*.

106. Capacity of Bodies for Heat. — If we place a kilogram of mercury and a kilogram of water in separate vessels on a hot stove, the mercury will become hot very much sooner than the water. This is because it takes more heat to heat water than mercury, or, to use

scientific language, because the *capacity* of water for heat is greater than that of mercury.

If we mix 1 kg. of water at 40° with 1 kg. of water at 20° , the temperature of the mixture will be 30° . The heat which leaves the kilogram of water at 40° in falling from 40° to 30° is just sufficient to raise a kilogram of water from 20° to 30° . But if we pour a kilogram of lead shot at 40° into a kilogram of water at 20° , the temperature of the water will be raised to only about 20.57° . In other words, a kilogram of lead in cooling from 40° to 20.57° furnishes only enough heat to raise a kilogram of water from 20° to 20.57° , — a little more than half a degree. Or, stated in another way, the quantity of heat that will raise a given quantity of water ($20.57 - 20 =$) 0.57 of a degree will raise an equal quantity of lead ($40 - 20.57 =$) 19.43 degrees.

Water outranks all other substances except hydrogen in its capacity for heat. The quantity of heat that raises a kilogram of water from 0° to 100° would raise a kilogram of iron from 0° to about 800° , or to a red heat. Conversely, a kilogram of water in cooling from 100° to 0° gives out as much heat as a kilogram of iron gives out in cooling from about 800° to 0° .

Water is a great equalizer of climatic temperature. On account of its great capacity for heat, water becomes heated very slowly and cools very slowly. Hence, the climate in the vicinity of large bodies of water is much less subject to extremes of temperature than places that are remote from water fronts.

107. Specific Heat. — The *specific heat* of a substance is the ratio of the quantity of heat required to raise the temperature of a given mass of the substance 1 degree to the quantity of heat required to raise the temperature of an equal mass of water 1 degree. The statement that the specific heat of mercury is 0.034 means that

it takes 0.034 as much heat to raise a given mass of mercury a certain number of degrees as to raise an equal mass of water the same number of degrees. The specific heat of any substance is numerically equal to the number of calories required to raise a kilogram of that substance 1 centigrade degree. For example, it requires 0.034 of a calorie to raise the temperature of 1 kg. of mercury 1 centigrade degree.

108. Method of determining Specific Heat. — A known mass, m_s (in kilograms), of the substance of which the specific heat is required is heated to a known temperature, t_s (C.); then it is mixed with (or immersed in) a known mass of water, m_w , at a lower temperature, t_w , and as soon as equilibrium of temperature is established the temperature of the mixture, t_m , is taken. Let s represent the specific heat of the substance sought. Then the quantity of heat lost by the substance is $m_s s (t_s - t_m)$ calories; while that gained by the water is $m_w (t_m - t_w)$ calories. Now if no heat be lost during the operation, it is evident that

$$m_s s (t_s - t_m) = m_w (t_m - t_w);$$

whence,
$$s = \frac{m_w (t_m - t_w)}{m_s (t_s - t_m)}.$$

For example, take the case given in § 107; we find for lead

$$s = \frac{1 (20.57 - 20)}{1 (40 - 20.57)} = 0.029.$$

In accurate work allowance must be made for the heat absorbed by the vessel, called the *calorimeter*, which holds the water.

EXERCISES

(In the following exercises temperatures are given in the centigrade scale.)

1. If 800 g. of sheet copper at 90° be placed in 500 g. of water at 10° and the resulting temperature be 20° , what is the specific heat of copper?

2. If 1 kg. of lead shot at 98° be poured into 1 l. of water at 15° , what will be the resulting temperature? (Sp. h. of lead = 0.03.)

3. (a) If the average temperature of the water of Lake Michigan were raised some warm day from 10° to 13° , to what temperature would a lake of mercury having the same mass be raised on receiving the same amount of heat? (See Table of Specific Heat in Appendix.)

(b) Which "lake breeze" would become unbearable?

4. Why does the sand on the seashore become much warmer on a summer day than the surface of the adjacent waters?

5. A teakettle contains 3 l. of water at 12° ; how much heat will be required to raise it to the boiling point if the atmospheric pressure be 760 mm.?

6. (a) A piece of iron weighing 20 kg. loses how much heat in cooling from 80° to 40° ? (b) The same quantity of water would lose how much heat in cooling the same number of degrees?

SECTION IV

EFFECTS OF HEAT—CHANGE OF VOLUME

109. Classification. — The effects of imparting heat to bodies may be classified as follows: (1) chemical effects; (2) electrical effects; (3) change of volume; (4) change of state.

110. Chemical Effects. — Heat applied to a body often changes the composition of its molecules. In some cases there is a tendency to combination. Combustion is an

effect of high temperature, a certain temperature being required to start it. The small flame of a match is sufficient to cause illuminating gas and oxygen, one of the constituents of the air, to unite and burst into a brilliant flame. In some cases heat tends to separate molecules into their constituents. As an example, crumbs of bread placed on a hot stove soon break up into certain gases and carbon; the former mingle with the air, leaving a black mass of charcoal. All such changes, which involve a change in molecular structure, belong to the domain not of physical but of chemical science.

111. Electrical Effects. — Interesting electrical phenomena are producible by heat, as will be shown under the head of Thermo-Electrical Currents in the chapter on Electrokinetics.

112. Change of Volume. — It is this effect that chiefly commands our attention at present. With few exceptions, all bodies, whether solids, liquids, or gases, increase in volume when their temperature is raised. This result we should naturally expect when we reflect that a rise of temperature means an increase of molecular speed, in which case the molecules must hit one another harder blows and thereby drive one another farther apart and at the same time weaken the cohesion.

The following simple experiments will illustrate expansion produced by heat.

Experiment 1. — Apparatus used: a pair of inside and outside calipers (Fig. 103), and a metal tube at least an inch in diameter. Fit the tube tightly between the prongs *a* and *b* of the calipers; then heat the tube quite hot. The tube will not now pass

between the prongs until they are separated a little more. Thrust the tube into cold water and cool it. It will now pass between the prongs.

Fit the prongs *c* and *e* to the bore of the tube and heat the tube; the prongs now must be opened a little farther in order to fit the bore.

With the statement that "heat expands" is sometimes coupled the statement that "cold contracts." The latter statement evidently is untrue if by "cold" is meant an agent that produces contraction. Cold is a term of *negation*. It signifies merely a greater or less deficiency of heat as darkness signifies an absence of light. Since cold is not an agent that has an actual existence, we cannot with propriety say that it ever does anything. The cooling, *i.e.*, the diminution of molecular motion, simply makes it possible for *cohesion* to draw the molecules of a body a little closer together, and the body is said to *contract*.

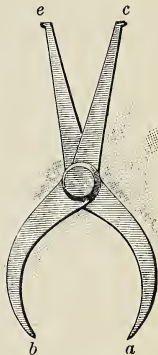


FIG. 103

Experiment 2. — Fig. 104 represents a thin brass plate and an iron plate of the same dimensions riveted together so as to form what is called a *compound bar*.

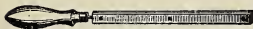


FIG. 104

Place the bar edgewise in a flame, dividing the flame in halves (one half on each side of the bar) so that both metals may be equally heated. The bar, which at first was straight, now bends, owing to the *unequal expansion* of the two metals on receiving *equal increments of temperature*. Brass, which is more expansible than iron, is now on the outer or convex side of the bar.

Experiment 3. — Fit stoppers tightly in the necks of two similar thin glass flasks (or test tubes) and through each stopper pass a glass tube about 60 cm. long. The flasks must be as nearly alike as possible. Fill one flask with alcohol and the other with water,

and crowd in the stoppers so as to force the liquids in the tubes a little way above the corks. Set the two flasks into a basin of hot water, and note that at the instant the flasks enter the hot water the liquids sink a little in the tubes, but quickly begin to rise, until, perhaps, they reach the tops of the tubes and run over.

When the flasks first enter the hot water they expand, and thereby their capacities are increased. Meantime, as the heat has not reached the liquids to cause them to expand, they sink momentarily to accommodate themselves to the enlarged vessel. As soon, however, as the heat reaches the liquids they begin to expand, as is shown by their rise in the tubes. The alcohol rises faster than the water. Roughly speaking, alcohol is about ten times as expansive as water. *Different substances, in both the solid and the liquid states, expand unequally on experiencing equal changes of temperature.*

Experiment 4.—Take a dry flask like that used in Experiment 3, insert the end of the tube in a bottle of water (Fig. 105), and apply heat to the flask; the inclosed air expands and comes out through the liquid in bubbles. After a few seconds withdraw the heat, keeping the end of the tube in the liquid; as the air left in the flask cools, its pressure decreases, and the water is forced by atmospheric pressure up the tube into the flask and partially fills it.

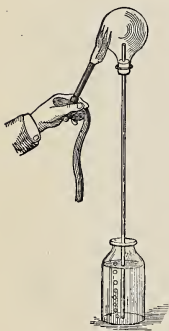


FIG. 105

113. Some Practical Consequences of Expansion and Contraction.—The forces exerted by metals when expanding and contracting are practically irresistible. Iron plates in engine boilers are bound tightly together in the following manner: iron rivets, heated red hot, are passed through holes in the plates and hammered till both heads closely grip the plates; the contraction of the rivets

on cooling binds the plates together with great force. In the process called “shrinking on the tires” of carriage wheels the tires

are expanded by heat till they slip on easily; as they cool, they contract and bind the wheels fast. The ends of steel rails on our railroads must have a little space between them, so that in hot weather they will not force one another out of line and occasion fearful accidents. For a similar reason steam pipes and hot-water pipes require the insertion of expansion joints.

114. Anomalous Expansion and Contraction. — Water presents a partial exception to the general rule that matter expands on receiving heat and contracts on losing it. If a quantity of water at 0° C. be heated, it contracts as its temperature rises, until it reaches 4° C., when its volume is least, *i.e.*, it has its *maximum density*. If heated beyond this temperature it expands, and at about 8° C. its volume is the same as at 0° . The mass of 1 cc. of pure water at 4° C. is 1 g. (§ 7).

The following table gives the volume of 1 g. of water at certain temperatures:

VOLUME OF 1 G. OF WATER AT ATMOSPHERIC PRESSURE

TEMPERATURE	STATE	VOLUME
— 10°	Ice	1.0897 cc.
0°	"	1.0909 "
0°	Water	1.0001 "
4°	"	1.0000 "
50°	"	1.0120 "
100°	"	1.0431 "
100°	Steam	1650. "
150°	"	1870. "

The anomaly in the expansion of water leads to important results in the economy of nature. In severely cold weather the upper layers of the water of ponds and lakes cooled by the air

and wind sink and cool the whole to 4° C. A further loss of heat makes the surface layers lighter, so that water between 4° and 0° floats on water at 4° ; consequently the water at the surface when it reaches 4° ceases to descend and cool the lower water below this point. Water being a very bad conductor of heat (§ 137), it takes a very long time for the deeper layers of water to part with their heat, and so, even in the hardest winters, the ice in temperate zones is seldom very thick, and the water at the bottom of deep lakes is seldom colder than 4° C. This irregularity in expansion occurs in no other liquid to an appreciable extent.

115. Expansion Coefficients. — The expansion which attends a rise of temperature depends not only upon the size of the body and upon its change in temperature, but upon a quantity peculiar to the substance itself, called its *expansion coefficient*. The so-called *linear expansion coefficient* is the increase of unit length per degree rise of temperature. Thus, suppose that a rod of metal of length l at temperature t° be heated and its length at t_1° becomes l_1 ; then, representing the linear expansion coefficient by c , we have, according to definition,

$$c = \frac{l_1 - l}{l(t_1 - t)},$$

a quantity which is nearly constant for the given substance, but which has different values for different substances. (See Table of Expansion Coefficients in the Appendix.)

In the expansion of fluids we have to do only with increase of volume, called *volume* or *cubical* expansion. A *volume expansion coefficient* is the increase of unit volume per degree rise of temperature. This is approximately $3c$, or three times the linear expansion coefficient,

and may be taken as such for most practical purposes. Likewise, the surface or superficial expansion coefficient is approximately 2 *c*.

Not only do the expansion coefficients of liquids and solids vary with the substance, but the coefficient for the same substance varies with the temperature, being greater at high than at low temperatures. Hence, in giving the expansion coefficient of any substance it is customary to give the *mean* coefficient through some definite range of temperature, as from 0° to 100° C.

EXERCISES

(Use expansion coefficients found in the Appendix.)

1. A certain brass rod is 10 feet long at 20° C. What is its length at 90° ? *Ans.* 10 feet, 0.16 inch.
2. A steel rail is 20 feet long at 30° C. How much shorter is it at 0° ? *Ans.* About 0.1 inch.
3. A rod of a certain metal is 100 feet long at 10° C. and 100.15 feet long at 85° . What is the expansion coefficient of that metal?
4. The standard platinum meter rod is 1000 mm. long at 0° C. What is its increase of length at 100° ?
5. The volume of a mass of copper at 100° C. is 850 cc. What is its volume at 10° ? *Ans.* 846.1 cc.
6. The area of one side of a brass cube at 12° C. is 1 m.² What is the area of this side at 92° ?
7. Describe the changes in volume which water undergoes between 0° C. and 10° C.
8. Clocks lose time in summer and gain time in winter. Explain.
9. By which expansion, linear or volume, is temperature indicated by a mercury thermometer?
10. (a) How is the capacity of the bulb of a thermometer affected by a rise of temperature? (b) Is the apparent expansion of mercury in a thermometer greater or less than the real expansion?

SECTION V

CHANGES OF VOLUME CONTINUED—KINETIC THEORY OF
MATTER — CRITICAL TEMPERATURE — ABSOLUTE
TEMPERATURE — LAWS OF GASES

116. Kinetic Theory of Matter. — The theory that the molecules composing all bodies of matter are in perpetual motion is called the *kinetic theory of matter*. According to this theory, the molecules in gases are so far separated from one another that their motions are not generally influenced by molecular attractions. Hence, in accordance with the First Law of Motion, the molecules of gases move in *straight lines* until they collide with one another or strike against the walls of the containing vessel, from which they rebound and start on new paths.

117. Pressure of a Gas due to the Kinetic Energy of its Molecules. — Consider, then, what a molecular storm must be raging about us, and how it must beat against us and against every exposed surface. According to the kinetic theory, a gas exerts pressure upon the interior surfaces of the vessel which confines it, in consequence of the incessant strokes of the molecules of the gas upon the surfaces (§ 29), the strokes following one another in such rapid succession that the effect produced cannot be distinguished from continuous pressure. Upon the energy of these strokes and upon their frequency must depend the amount of pressure. But we have learned that on the kinetic energy of the molecules depends that condition of a gas called its *temperature*; so it is apparent that *the pressure of a given quantity of gas varies with its*

temperature. Again, as at the same temperature the number of strokes per second must depend upon the number of molecules in the unit of space, it is apparent that *the pressure varies with the density.*

118. Critical Temperature.—Up to the year 1877 there were six gases which had resisted all attempts to liquefy them. These were called “the permanent gases.” But this distinction has since disappeared, for under great pressure and through the agency of improved mechanical devices every one of these has been reduced to the liquid, and even to the solid, state. The expression *liquid air* is now familiar to all.

The gases must first be deprived of much of their molecular energy. For each gas there is a temperature called the *critical temperature*, above which it is not possible to liquefy the gas under any pressure, however great. For example, the components of the atmosphere have different critical temperatures: oxygen, -118°C. ; nitrogen, -146°C. ; argon, -121°C. The pressures under which they liquefy at these temperatures are, respectively, 59, 35, and 51 atmospheres. At lower temperatures less pressure is required; at higher temperatures these gases can never be liquefied. Above the critical temperature a gas is said to be a *true gas*, since it is not condensable into a liquid by pressure only. The term *vapor* is usually applied to the gaseous state of such substances as water, alcohol, ether, etc., whose critical temperatures are relatively high.

119. Absolute Zero.—The zeros found on our thermometers were chosen by man. The *absolute zero* is

independent of the choice of man ; it implies a *total absence of heat*. At the absolute zero the molecules must be *at rest*, and gases (if they may be called such) exert no pressure. This temperature has never been attained, but it may be estimated or even calculated with great accuracy.

The French physicist Charles discovered in 1786 the important fact that *the volume of a given mass of air increases for each degree of rise in temperature and decreases for each degree of fall in temperature, provided the pressure be constant, by the constant fraction $\frac{1}{273}$ of its volume at 0° C.* At this rate, if a mass of air could be cooled down from 0° C. to -273° C. and should remain a perfect gas throughout, it would lose $\frac{273}{273}$ of its volume. At this point it is supposed that the air particles would lose all their activity and energy, which alone give volume and pressure to a mass of gas. This is assumed, therefore, to be the absolute zero of temperature. Before reaching this temperature, however, every gas, as we have learned above, becomes a liquid. Although it is impossible actually to cool a body down to the absolute zero, it is interesting to note that a temperature as low as -250° C. has been obtained by allowing liquid hydrogen to boil at reduced pressure. (See Methods of producing Cold Artificially, Section VIII.)

120. Absolute Temperature. — Absolute temperature is that measured from the absolute zero. Absolute temperature is found by adding 273 to any given temperature as indicated by a centigrade thermometer, or 459.4 to the temperature as indicated by a Fahrenheit thermometer.

Fig. 106 furnishes a comparative view of both the arbitrary and the absolute thermometric scales, expressed in both centigrade and Fahrenheit degrees.

121. Laws of Gases.—Our discussions hitherto would lead us to conclude that rise in temperature in a body of gas tends not only to an increase of volume but to an increase of pressure in that body. Now as a result of careful experimentation the following laws for gases have been determined:

(1) The volume of a given mass of gas at constant pressure is proportional to its absolute temperature.

This is a deduction from the discovery of Charles given above, and is known as the *Law of Charles*.

Likewise (2) the pressure of a given

mass of gas whose volume is kept constant is proportional to its absolute temperature.

Boyle's Law (§ 31) states that (3) at a constant temperature the volume of a given mass of gas is inversely proportional to its pressure.

	C.	F.	Abs. Temp. Cent. deg.	Abs. Temp. Fah. deg.
Tin melts	233°	451°	506°	910.4°
Water boils	100°	212°	373°	671.4°
Alcohol boils	78°	172.4°	351°	631.8°
Ether boils	35°	95°	308°	554.4°
Ice melts	0°	32°	273°	491.4°
Mercury freezes	-38.8°	-37.9°	234.2°	421.5°
Alcohol freezes	-130.5°	-202.9°	142.5°	256.5°
Lowest temperature yet attained estimated to be about	-250°	-418°	23°	41.4°
	-273°	-459.4°	0°	0°

FIG. 106

By a combination of Boyle's Law with Charles' Law we obtain the following comprehensive law:

(4) The product of the volume and pressure of a mass of gas is proportional to its absolute temperature.

It must be understood that the above laws are true only on the condition that the gas under consideration is not near the state of liquefaction.

EXERCISES

1. Find, in both centigrade and Fahrenheit degrees, the absolute temperatures at which oil of turpentine (see Table of Properties of Liquids in Appendix) boils and freezes.

2. At 0°C . the volume of a certain mass of gas under a constant pressure is 500 cc. (a) What will be its volume if its temperature be raised to 75°C .? (b) What will be its volume if its temperature become -20°C .?

3. If the volume of a mass of gas at 20°C . be 200 cc., what will be its volume at 30°C .?

4. To what volume will a liter of gas contract if cooled from 30°C . to -15°C .?

5. One liter of gas under a pressure of one atmosphere will have what volume, if the pressure be reduced to 900 g. per square centimeter, while the temperature remains constant?

6. The volume of a certain mass of air at a temperature of 17°C ., under a pressure of 800 g. per square centimeter, is 500 cc. What will be its volume at a temperature of 27°C ., under a pressure of 1200 g. per square centimeter? *Solution:* 17°C . is equivalent to 290° abs. temp.; 27°C . is equivalent to 300° abs. temp. Then, $290 : 300 :: 500 \times 800 : x \times 1200$. Whence, $x = 344.8$ cc. *Ans.*

SECTION VI

EFFECTS OF HEAT CONTINUED—CHANGE OF STATE

122. Fusion.—Every change of state in matter is associated with either a disappearance or a generation of heat; and it is usually necessary either to increase or to decrease the heat during the change. Many substances are capable of existing in any one of the three states, solid, liquid, or gaseous. Which one of these states a given substance exists in depends usually on its temperature and the pressure upon it.

Heat tends to weaken cohesion; consequently, the rigidity and the tenacity of solids are generally lessened with rise of temperature. Heat applied to solids tends to melt or fuse them. Many substances, under normal pressure, change at a definite temperature, called the *fusing point*, from the solid to the liquid state, or *vice versa*, so that when their temperatures are above this point they are liquids, and when below this point they are solids. In fact, at 0° C. water substance can exist in any one of three distinct states, as a solid, a liquid, or a vapor. Under ordinary pressure ice cannot be made warmer than 0° C.

Experiment 1.—Put a lump of ice as large as your two fists into boiling water; when it is reduced to about one fourth its original size skim it out. Wipe the lump, and place one hand on it and the other on a lump to which heat has not been applied; you will not perceive any difference in their temperatures. *The temperature of ice at its fusing point does not change while melting.*

123. Regelation.—In changes of state from solids to liquids, or *vice versa*, we seldom concern ourselves much

with the work done by or against exterior pressure. An interesting exception, however, is to be noted in the case of melting ice. The melting point of ice is lowered a very little (0.007° C. per atmospheric pressure) by exterior pressure. This leads to some important consequences. If two pieces of ice be pressed together, the ice will melt at the points of contact; and when the pressure is relieved, the water flowing around these points will freeze and thus the pieces become welded together. This operation is called *regelation*. By this process hard snowballs are made from loose snow. If snow be subjected to great pressure in molds, it is con-

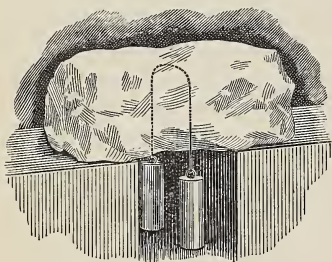


FIG. 107

verted into solid ice. It is in this way that glacier ice is formed from snow, the stratum at the bottom receiving the pressure of the great accumulation of snow above.¹

If a block of ice have heavy weights hung upon it by a wire which is

passed over the block (Fig. 107), the pressure will melt the ice below the wire. The water thus formed is forced above the wire and freezes as the pressure is relieved, so that the wire appears to traverse the block without cutting it.

When lumps of ice are pressed through a narrow passage they crumble, melt, and re-cohere, so that the whole mass *flows*, much as if it were a viscous fluid, a circumstance which is employed in explaining the *flow of glaciers*.

¹ In this connection the pupil is advised to read Tyndall's *The Forms of Water*.

124. Vaporization. — Water left in an open vessel gradually “dries away,” that is, changes to an invisible vapor and becomes diffused through the air. This process is called *vaporization* and its converse is called *condensation*, or *liquefaction*.

A slow vaporization, which takes place only at the exposed surface of a liquid, is called *evaporation*. A rapid process, which may take place throughout the liquid, but usually is most rapid at the point where heat is applied, is called *boiling*, or *ebullition*.

125. Evaporation. — *Rapidity of evaporation depends on the nature of the liquid* — alcohol evaporates faster than water; *on the temperature of the liquid* — warm water evaporates faster than cold water; *on the temperature of the air above the liquid* — heated air will hold more vapor than cold air, consequently evaporation is more rapid into hot air; *on the change of the air over the liquid* — water evaporates more quickly on windy days than when the air is still; *on the extent of free surface exposed* — a pint of water sprinkled over a floor evaporates very quickly; and *on the pressure on the surface of the liquid* — sugar refiners hasten evaporation by placing sugar solutions in vacuum pans where pressure is reduced by means of air pumps. Liquids that evaporate quickly are called *volatile liquids*. Evaporation takes place at all temperatures. Even ice and snow evaporate. The laundress does not hesitate to hang clothes to dry even though she expects them to freeze quickly. Snow heaps and blocks of ice become reduced in mass at a freezing temperature.

126. Boiling Point dependent upon Pressure. — In evaporation, molecules fly from the surface of the liquid and mingle with the particles of the air; but in boiling, the vapor, more commonly called *steam*, escaping too rapidly to become immediately diffused in the air, drives back the air a little way. Not until the steam acquires a pressure a trifle greater than that of the atmosphere can a liquid begin to boil. The greater the external pressure to be overcome, the greater must be the pressure, *i.e.*, the higher the temperature, of the steam.

In every case the boiling point is an indication of the heat energy necessary to overcome cohesion in the liquid and the pressure on its surface in order that the molecules may pass off as a vapor.

Experiment 2. — Half fill a glass flask with water. Boil the water over a Bunsen burner; the steam will drive the air from

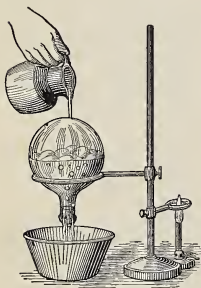


FIG. 108

the flask. Withdraw the burner, quickly cork the flask very tightly, invert it, and pour cold water upon the part containing steam, as in Fig. 108. The water in the flask, though cooled several degrees below the usual boiling point, boils again violently. The application of cold water diminishes the pressure of the steam, so that the pressure upon the water is diminished, and the water boils at a temperature lower than its normal boiling point.

Experiment 3. — In a beaker half full of distilled water suspend a thermometer so that the bulb will be covered by the water and yet be at least 2 inches above the bottom of the beaker. Apply heat to the

beaker, and observe any changes of temperature that may occur, both before and after boiling begins. The mercury in the thermometer rises continuously until the water begins to boil, but soon after, that is, as soon as thermal equilibrium between the mercury and water is established, it ceases to rise, thereby showing that the temperature of the water remains constant notwithstanding the continuous application of heat to it.

It is found that (1) *for a given pressure* (for example, that of the atmosphere at 760 mm.) *every liquid has a definite boiling point* called the *normal boiling point* for that liquid; (2) *this boiling point remains constant after boiling has begun*; (3) *the boiling point of a liquid increases with the pressure*. A rise of 27 mm. in the height of a barometric column is attended with a rise of about 1° C. in the boiling point of water boiled in an open vessel.

The boiling point of water varies with the altitude of places, in consequence of the change in atmospheric pressure. At the height of 3 miles above sea level, water cannot be got hot enough in an open vessel to coagulate the white of an egg. Roughly speaking, a difference of altitude of 900 feet causes a variation of 1° C. in the boiling point.

127. Distillation. — This is a process by which a liquid is obtained by evaporation in a state of purity. If two liquids are mixed, for example water and alcohol, the more volatile of the two will be vaporized first, leaving the less volatile behind; or if there are impurities in water, for example salts in solution, the liquid evaporates and leaves the solid matter. At sea, fresh water for drinking purposes may thus be obtained from sea water.

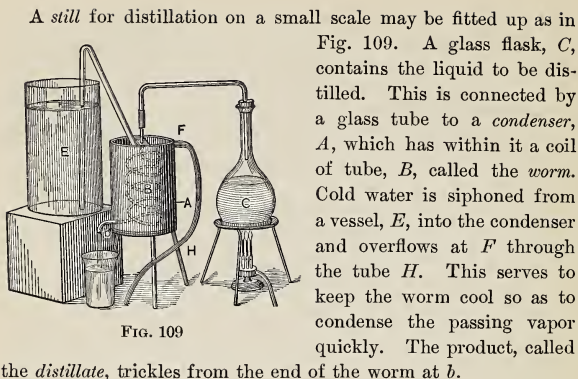


FIG. 109

SECTION VII

LATENT HEAT

128. Latent Heat of Fusion.—Every one knows that, in general, heat applied to a body raises its temperature. Two exceptions to this rule we have just studied under the head of *melting* and *boiling*.

As we learned in § 122, the temperature of a solid while melting does not change. It would appear that all the heat applied to ice, for instance, while it is melting is expended in changing it from a solid at 0°C. to a liquid at 0°C. Heat is a form of energy, and when it is applied to a body and does work in changing the state of that body, it assumes some other form or state of energy. About the form of energy which it assumes we know little except that it is in a potential state.

For more than a century we have been accustomed to say that heat that disappears in melting solids becomes *latent*. This term signifies *hidden*, and is still apropos as regards our knowledge.

Everybody who has watched a lump of ice slowly melting over a hot fire, or has observed that many days of warm sunshine in the spring are required to melt away a bank of snow, must be convinced that a large quantity of heat is spent in melting ice. The *latent heat of fusion* of a substance is the number of calories that must be applied to a kilogram of that substance to change it from a solid to a liquid state without a change of temperature.

If a kilogram of water at 100°C . be poured upon a kilogram of water at 0°C . and they be stirred, the resulting temperature of the mixture will be 50°C . That is, a given quantity of water falling in temperature 1° furnishes just heat enough to raise the temperature of an equal quantity of water 1° . But if a kilogram of water at 100°C . be poured upon a kilogram of small ice chips or snow at 0°C . and the temperature of the mixture after the ice is melted be taken, it will be found to be approximately 10°C . Now to raise the kilogram of water resulting from the melted ice from 0°C . to 10°C . requires 10 calories of heat, which are furnished by the kilogram of hot water in cooling from 100°C . to 90°C . But the hot water cools to 10°C . It is evident, then, that the heat yielded by the water in cooling from 90° to 10° is rendered latent in melting the ice. The latent heat of fusion of ice is, therefore, approximately 80 calories. The latent heat of fusion

of other substances may be found in the Table of Properties of Solids in the Appendix.

129. Transformation of Heat Reversible. — Heat that raises the temperature of bodies is called *sensible heat*. When sensible heat disappears or is rendered latent in changing the state of a body, whether from a solid to a liquid, or from a liquid to a vapor, it is said to be spent in doing *interior work* among the molecules. In the case of boiling, however, a portion of the heat that disappears must be consumed in overcoming atmospheric pressure. Heat that has become latent is, therefore, not heat, but a form of *molecular potential energy*.

We learned in § 81 that potential energy is transformed into kinetic energy “by the return of the particles to their original positions.” Consequently, we are prepared to expect that when water freezes or any liquid solidifies, its latent heat, or molecular potential energy, becomes sensible heat. While 1 kg. of water freezes, 80 calories of sensible heat are generated,—enough heat to raise the temperature of 1 kg. of water from 0° C. to 80° C. As heat is developed while water freezes it must be “given off” in order to allow the freezing to go on. As the diffusion is necessarily slow, so freezing must be slow; and this slow development of heat and its immediate dispersion accounts for the fact that we are seldom made conscious of the development of heat during freezing.

Farmers sometimes turn to practical use this well-known phenomenon. Anticipating a cold night, they carry tubs of water into cellars to be frozen. The heat generated thereby, although of a low temperature, is sufficient to protect vegetables which freeze at a lower temperature than water.

130. Latent Heat of Vaporization. — We have also learned (§ 126) that the temperature of a liquid remains

constant after boiling begins. If heat be applied to water, for instance, its temperature rises until it reaches its boiling point, when there is a halt. The heat received by a liquid while it is converted into a vapor is rendered latent. The quantity of heat required to convert a kilogram of water at 100°C. into steam without altering its temperature is called the *latent heat of vaporization of water*. This, in turn, is the same as the quantity of sensible heat generated and set free by the condensation of 1 kg. of steam.

Let a known quantity of water be placed in a closed flask, *A* (Fig. 110), and boiled, the steam passing through a tube into a beaker, *B*, containing a known quantity of cold water having a known temperature at the beginning. The heat rendered latent in converting the water into steam will be reconverted into sensible heat as the steam is condensed on entering the cold water. If proper care be exercised (for details of this operation, see the author's *Elements of Physics*), data may be obtained from which may be calculated the latent heat of vaporization of water.

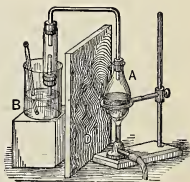


FIG. 110

For example, suppose that the quantity of water vaporized is 0.1 kg. and that the quantity of water in the beaker is 1 kg. and its temperature is 15°C. at the beginning and 68.6°C. at the close. Let x represent the quantity of heat rendered latent in converting 1 kg. of water into steam; then $0.1 \times x =$ the quantity of heat rendered latent in this case, and $1 \times (68.6 - 15) =$ the quantity of heat imparted to the water in the beaker. Then, since the two quantities of heat are equal,

$$0.1 \times x = 1 \times (68.6 - 15),$$

whence $x = 536$, the latent heat of vaporization of water; *i.e.*, it requires 536 calories to convert 1 kg. of water at 100°C. into

steam at the same temperature. We reason that the amount of work done in boiling water is very great, as is shown by the amount of heat consumed.

Steam is a most convenient vehicle for the conveyance of heat of vaporization, *i.e.*, potential energy, from the boiler to distant rooms requiring to be heated. The heat generated by the condensation of the steam is imparted to the radiator, and this in turn imparts it to the apartment. For every kilogram of steam condensed in the pipes of the radiator, 536 calories, or heat enough to raise 5.36 kg. (about 12 pounds) of ice water to the boiling point, are generated.

EXERCISES

1. How are we protected from a great freshet on any warm day when the ground is heavily covered with snow?

2. Does the water in the boilers of steam engines suddenly flash into steam on reaching the boiling point? Why?

3. (a) How much heat is required to change a kilogram of ice at 0° C. into steam at 100° ? (b) How much of this heat is rendered latent and (c) how much remains sensible heat?

4. Let 40 kg. of water freeze in a cellar whose temperature is below centigrade zero. How much heat will be given out in the cellar?

5. Let 5 kg. of steam at 100° C. pass through a steam radiator in a room, be condensed, and leave the radiator as water at 98° C. How much heat will be radiated into the room?

6. How much ice at 0° C. will 4 kg. of water at 90° C. melt?

7. If 2 kg. of water at 70° C. be poured upon 500 g. of ice at 0° , what will be the temperature of the mixture after the ice is melted?

8. How much water at 100° C. is required to melt 1 kg. of ice at 0° C.?

9. Give a reason why the temperature of the air usually rises soon after snow commences to fall.

SECTION VIII

METHODS OF PRODUCING COLD ARTIFICIALLY

131. Artificial Cold. — A body becomes cold only by losing heat. As heat passes only from warmer to colder bodies, it is evident that the temperature of a body cannot fall below that of surrounding bodies — for example, below the temperature of other bodies in the same room — by the natural process of imparting heat to its neighbors. The temperature of a body, then, can be reduced below that of its neighbors only by some artificial means.

The fact that heat is consumed in the conversion of solids into liquids, and of liquids into vapors, is turned to practical use in many ways for the purpose of producing *cold artificially*.

132. Heat consumed in dissolving; Freezing Mixtures.

Experiment 1. — Prepare a mixture of two parts, by mass, of pulverized ammonium nitrate and one part of ammonium chloride. Take about 75 cc. of water (not warmer than 8° C.) and into it pour a large quantity of the mixture, stirring it while dissolving with a test tube containing a little cold water. The water in the test tube will be quickly frozen. A finger placed in the solution will feel a painful sensation of cold, and a thermometer will indicate a temperature of about - 10° C.

One of the most common freezing mixtures, much used in making ice cream, consists of three parts of snow or broken ice and one part of common salt. The affinity of salt for water tends to produce liquefaction of the ice, and the resulting liquid dissolves the salt, *both operations consuming heat*.

133. Heat consumed in Evaporation. — The heat consumed in vaporization is greater than that consumed in liquefaction; for example, in the case of water, as we have seen, it is greater in the ratio of 536 : 80. Hence, evaporation is the more efficient means of producing extremely low temperatures. Whatever tends to hasten evaporation (see § 125) tends to accelerate the reduction of temperature. Through the consumption of its own heat in the process of evaporation, the liquid itself becomes colder, and then reduces the temperature of all objects in its neighborhood. The more volatile the liquid employed, the more rapid is the consumption of heat, other things being equal.

Experiment 2. — Fill the palm of the hand with ether; the ether quickly evaporates and produces a sensation of cold. Ether is not colder than neighboring bodies except when it is allowed to evaporate.

Experiment 3. — Wrap a wad of cotton batting about the bulb of a thermometer, wet the batting with ether, and swing the thermometer swiftly through the air a few times and note the fall of temperature as indicated by the thermometer.

134. Heat consumed by the Expansion of Gases. — If a gas be allowed to expand against pressure, work is done, heat is consumed in doing it, and the temperature of the gas is lowered. In steamships which make long voyages the refrigerators constructed for conveying perishable material like meat are kept cold by this process.

Air is compressed by steam power to about one fourth its normal volume. This itself heats the air, since by this process the work required for compression is converted into heat energy.

(See § 98.) The air is then cooled by contact with pipes kept cool by cold water flowing through them. The air is then allowed to expand into the refrigerating chamber, and its temperature is lowered; for it must be understood that in order that a compressed gas may resume its normal volume against pressure, an amount of heat energy is required equivalent to the molar energy which effected the compression.

EXERCISES

1. If you hold your hand about 30 cm. from your mouth and blow strongly on it, you experience a cool sensation. Explain.
2. How are we benefited on warm days by perspiration?
3. When a bottle containing a liquid charged with carbonic acid is opened suddenly there appears a fog in the neck of the bottle. Explain.
4. Heated air rising from the surface of the earth becomes in the upper regions very cold. Explain.

SECTION IX

HYGROMETRY

135. Dew-Point. — *Hygrometry* treats of the state of the air with regard to the water vapor it contains. A given volume of air, for example a cubic meter, can hold only a limited quantity of water vapor. This quantity depends on the temperature of the air. The capacity of air for vapor increases rapidly with the temperature, being nearly doubled by a rise of 10 centigrade degrees. On the other hand, if air containing a given quantity of water vapor be cooled, it will continually approach and finally reach *saturation*, since the lower the temperature, the less the capacity for water vapor. It is evident that

air saturated with vapor cannot have its temperature lowered without the condensation of some of the vapor into a liquid, which will appear, according to location and condition of objects within it, as *dew*, *fog*, or *cloud*. The temperature at which this condensation occurs is called the *dew-point*. The dew-point may be defined as the *temperature of saturation* for the quantity of water vapor actually present. The greater the quantity of water vapor present, the higher is its dew-point. Capacity for water vapor depends upon temperature; dew-point depends upon the quantity of water vapor present.

If the existing temperature be far above dew-point, it indicates that the air can contain much more water vapor than there is in it at the time, and the air is said to be *dry*. The heat of a stove dries the air of a room without destroying any of its water vapor. In such a room the lips, tongue, throat, and skin experience a disagreeable sensation of dryness, owing to the rapid evaporation which takes place from their surfaces.

EXERCISES

1. To what is the "dampness of night air" due?
2. How do "air-tight stoves" and furnaces dry the air in apartments?
3. (a) How is the "sweat" sometimes seen on cold objects such as ice pitchers, tumblers, etc., caused? (b) When the sweat collects quickly and abundantly what does it indicate respecting the dew-point of the air? (c) In such cases what slight change of temperature in the air will cause rain?
4. Which are the more favorable to deposition of dew, windy or still nights? Why?
5. The air in a certain room is said to be "dry." (a) Does this indicate that the dew-point in the room is *high* or *low*? (b) If the temperature of the air in the room should fall, how would its humidity be affected? (c) Would the dew-point be changed?

SECTION X

DIFFUSION OR TRANSFERENCE OF HEAT

136. Three Processes of Diffusion. — There is always a tendency to *equalization of temperature*; that is, heat has a tendency to pass from a warmer body to a colder, or from a warmer to a colder part of the same body, until there is an equality of temperature. There are three processes of diffusion of heat, — *conduction*, *convection*, and *radiation*.

137. Conduction.

Experiment 1. — Place one end of an iron wire about 10 inches long in a lamp flame, and hold the other end in the hand. Heat gradually travels from the end in the flame toward the hand. Apply your fingers successively at different points nearer and nearer the flame; you find that the nearer you approach the flame, the hotter the wire is.

The flow of heat through an unequally heated body, from places of higher to places of lower temperature, is called *conduction*; the body through which it travels is called the *conductor*. The molecules of the wire in the flame have their motion quickened; they strike their neighbors and quicken their motion; the latter in turn quicken the motion of the next; and so on, until some of the motion is finally communicated to the hand and creates in it the sensation of heat.

Experiment 2. — Fig. 111 represents a board on which are fastened, by means of staples, four wires: (1) iron, (2) copper, (3) brass, and (4) German silver. Place a lamp flame where the wires meet. In about a minute run your fingers along the wires

from the remote ends toward the flame, and see how near you can approach the flame on each without suffering from the heat.

Make a list of these metals, arranging them in the order of their conductivity.

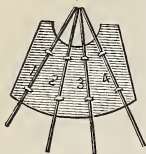


FIG. 111

Some substances conduct heat much more rapidly than others. The former are called *good conductors*, the latter *poor conductors*. Metals are the best conductors, though they differ widely among themselves, as our experiment shows.

Iron and marble, which are good conductors, feel colder to the touch of the hand than wood, carpet, and other poor conductors, because they conduct heat away from the hand faster. On the other hand, if these substances have a temperature higher than that of the hand, the latter will feel hotter than the former, because they conduct heat *to* the hand more rapidly. Handles of cooking utensils are made of non-conducting material to protect the hand from heat.

Experiment 3. — Nearly fill a test tube with water, and hold it somewhat inclined (Fig. 112), so that a flame may heat the part of the tube near the surface of the water. Do not allow the flame to touch the part of the tube that does not contain water. The water may be made to boil near its surface before any change of the temperature at the bottom will be perceived.

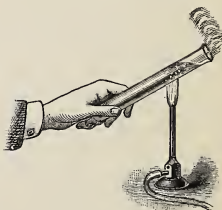


FIG. 112

Liquids are extremely poor conductors. Gases conduct heat practically not at all. Our clothing does not afford us heat in cold weather; it is, indeed, colder than our bodies. It simply checks the escape of the heat of our bodies. This is accomplished in part by the poorly conducting fibers of the clothing, but more by the air

spaces in the meshes of the cloth and by the layer of air confined between the clothing and our bodies. The protection obtained from the escape of heat from our houses by the use of double windows is little due to the thin glass which intervenes; it is due almost entirely to the body of confined non-conducting air inclosed between the windows. Snow is a great protection to vegetation from the severe cold of winter on account of the air confined in the spaces between the crystals.

138. Convection in Gases. — Conduction takes place gradually and slowly at best from particle to particle, the body and its particles being relatively at rest. *Convection* takes place when the body moves or when there is relative motion between its parts, the heat in either case being *conveyed* from one place to another.

Experiment 4. — Cover a candle flame with a glass chimney (Fig. 113), blocking the latter up a little way so that there may be a circulation of air beneath. Hold smoking touch-paper near

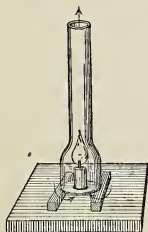


FIG. 113

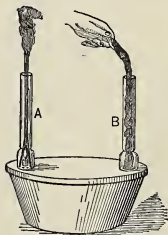


FIG. 114

the bottom of the chimney; the smoke seems to be *drawn* with great rapidity into the chimney at the bottom; in other words, the office of the chimney is to create what is called a *draught* of air.

Experiment 5. — Place a candle within a circle of holes cut in the cover of a vessel, and cover it with a chimney, A (Fig. 114).

Over an orifice in the cover place another chimney, *B*. Hold a roll of smoking touch-paper over *B*. The smoke descends this chimney and passes through the vessel and out at *A*. This illustrates the method often adopted to produce a ventilating draught through mines. Let the interior of the tin vessel represent a mine deep in the earth, and the chimneys two shafts sunk to opposite extremities of the mine. A fire kept burning at the bottom of one shaft will cause a current of air to sweep down the other shaft and through the mine, and thus keep up a circulation of pure air through the mine.

The cause of the ascending currents is evident. Air, on becoming heated, expands rapidly and becomes much rarer than the surrounding colder air; hence it rises, much like a cork in water, while cold air pours in laterally to take its place. In this manner winds are created. Sea and land breezes are convection currents.

Ventilation, or the process by which a proper supply of fresh air is maintained in our living apartments, is intimately connected with convection inasmuch as ordinarily it is through the latter that the former is secured. The heating apparatus should be so arranged as to produce, in the most efficient manner, convection currents that will expel foul air and introduce fresh air.



FIG. 115

139. Convection in Liquids.

Experiment 6. — Fill a small thin glass flask with boiling hot water colored with a teaspoonful of ink, put in the stopper, and lower the flask deep into a tub, pail, or other large vessel filled with cold water (Fig. 115). Withdraw the stopper, and the hot, rarer, colored water will rise from the flask, the cold water descending into the flask. The two currents passing into and out of the neck of the flask are easily distinguished. The colored

liquid marks distinctly the path of the heated convection currents through the clear liquid, and makes clear the method by which heat, when applied at the bottom of a body of liquid, becomes rapidly diffused through the entire mass, notwithstanding that liquids are poor conductors.

It is by similar convection currents that the warming of buildings by hot water is effected. Water heated in a boiler in the basement rises through pipes to the radiators in the rooms above; there it gives heat to the air of the room, and, after being thus cooled, returns by other pipes leading from the radiators to the boiler. Ocean currents, *e.g.*, the Gulf Stream, are convection currents. The warmer portions of the waters flow away from the tropical toward the polar latitudes, while at greater depths the cold waters of high latitudes flow back toward the tropics.

140. Radiation. — In *radiation* a hotter body loses heat, and a colder body is warmed, through the transmission of wave motion in a medium called the ether, *which is not itself heated thereby*. This mode of transmission of energy is the most important of all, and will be treated in a future chapter.

EXERCISES

1. (a) For what is a fire-proof safe used? (b) a refrigerator? (c) a steam jacket?
2. Why do the cork handles on bicycles feel warmer in winter and colder in summer than the metallic portions?
3. Which furnish us greater protection against extremes of temperature, tightly fitting or loosely fitting clothes and shoes?
4. In what ways does the air in a room obtain heat from a stove?
5. In what way does snow protect vegetation in winter from killing frosts?
6. How is heat diffused in fluids?
7. Place a door opening from a warm room to a cold room ajar. Hold a candle flame at the top, middle, and bottom of the passage. Observe and explain the currents of air.

SECTION XI

THERMODYNAMICS

141. Thermodynamics defined.— *Thermodynamics* treats of the relation between heat and molar work. One of the most important of recent discoveries in science is *the equivalence of heat and work*; that is, that *a definite quantity of molar work, when transformed without waste, yields a definite quantity of heat*; and, conversely, that *this heat, when transformed without waste, can perform the original quantity of molar work*.

142. Transformation, Correlation, and Conservation of Energy.— The proof of the facts just stated was one of the most important steps in the establishment of the grand twin conceptions of modern science: (1) that *all kinds of energy are so related to one another that energy of any kind can be transformed into energy of any other kind*, — known as the doctrine of the CORRELATION OF ENERGY; (2) that *when one form of energy disappears its exact equivalent in another form always takes its place, so that the sum total of energy is unchanged*, — known as the doctrine of the CONSERVATION OF ENERGY.

The whole drama of the universe consists in transfer-ences and transformations of energy; all natural phenomena are due to them, yet creation and annihilation of energy are not possible through any agency known to man. Energy is often wasted in that it goes where it is not needed, but it is never annihilated. Another great law of conservation may be mentioned in this connection. Chemistry teaches that there is a conservation of matter,

i.e., that matter is neither creatable nor annihilable through any known agency or process.

143. Mechanical Equivalent of Heat. — Assured that heat is a form of energy, Dr. Joule of England undertook (1840) to ascertain the numerical relation between the units of heat and those of molar work. He arranged a paddle wheel in a vessel of water so that the wheel was made to rotate by means of a descending weight. Placing a thermometer in the water, he found that the longer the water was stirred, the warmer it became. He measured the work done by the descending weight and the corresponding heat produced by the paddle turning in the water, and determined the ratio between the two quantities.

By a similar method but with improved details Rowland of Baltimore repeated (1879) the experiment with the greatest care that has ever been exercised and obtained for a result the following, which differs but little from the result obtained by Joule:

$$1 \text{ calorie} \approx 427 \text{ kgm.};$$

that is, 427 kgm. of work if converted into heat would raise the temperature of 1 kg. of water through 1 centigrade degree.

EXERCISES

1. Let the pupil take a survey of the facts he has gleaned thus far relating to heat, and argue therefrom that the modern theory of heat is valid.

2. If a body weighing 20 kg. fall 80 m. in a vacuum, how much heat will be generated when it is stopped?

3. How much molar work may be done by 5 calories of heat if none is wasted?

SECTION XII

STEAM ENGINE

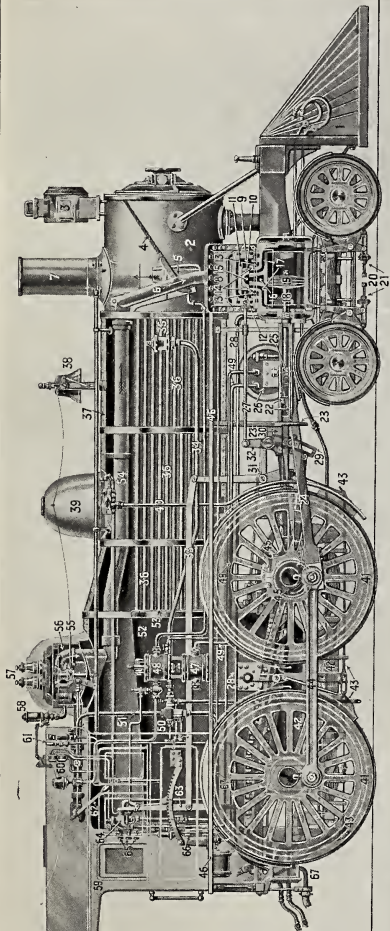
144. Description of a Steam Engine. — A steam engine is a machine in which the elastic force of steam is the motive agent. Inasmuch as the elastic force of steam is entirely due to heat, *the steam engine is properly a heat engine*; that is, it is a machine by means of which heat is continuously transformed into the energy of mass motion. The modern steam engine consists essentially of an arrangement by which steam from a boiler is conducted to each side of a piston alternately, and then, having done its work in driving the piston to and fro, is discharged from each side alternately, either into the air or into a condenser.

The steam engine furnishes to the scientific student a most interesting illustration of the transformation of heat into work. For the hot steam whose expansive force propels the piston falls in temperature and loses much of its energy as it does this work. To this is due the unbalanced force which drives the parts, for there is always steam both sides of the piston, but the steam doing work and the steam that has just done work have different temperatures.

145. The Locomotive.¹ — Few works of man have so commanded the admiration and excited the wonder of youth and

¹ For historical facts concerning the locomotive, the pupil is advised to read Smiles' work entitled *The Life of George Stevenson*. For the history and the theory of the steam engine in general, he may read with profit an article on this subject by Ewing in the *Encyclopædia Britannica*, and a bibliographical sketch of James Watt in the same work.

PLATE II — LOCOMOTIVE



Adapted from *Locomotive Engineering*, N.Y.

- | | | | |
|---------------------|-------------------------|---------------------------------|---------------------------|
| 1 Pilot | 35 Injector check valve | 47 Air cylinder of brake pump | 56 Dome |
| 2 Smoke box | 36 Flues | 48 Steam cylinder of brake pump | 57 Safety valves |
| 3 Headlight | 37 Boiler lagging | 49 Delivery to main reservoir | 58 Chimney whistle |
| 4 Netting | 38 Bell | 50 Injector | 59 Cab |
| 5 Exhaust pipe | 39 Sand box | 51 Injector steam pipe | 60 Pressure gauges |
| 6 Steam pipe | 40 Sand pipe | 52 Fire box | 61 Signal whistle |
| 7 Smokestack | 41 Driving wheels | 53 Tube sheet | 62 Throttle lever |
| 8 Cylinder saddle | 42 Ash pan | 54 Steam or dry pipe | 63 Reverse lever |
| 9 Steam chest valve | 43 Driver brakes | 55 Throttle valve | 64 Engineer's brake valve |
| 10 Balance plate | 44 Side or parallel rod | | 65 Gauge cocks |
| 11 Valve stem | 45 Eccentrics | | 66 Fire door |
| 12 Valve stem | 46 Running board | | 67 Feed pipe |

age as the *locomotive*. Not a few have stood beside the huge "iron horse" and wished that they might "see through it." The author, having this in mind, has ventured to digress from the beaten paths of text-books and to produce a cut of a modern locomotive without giving a description thereof, which the prescribed limits of this book do not permit. Plate II represents a locomotive so dismantled that the pupil may see much of its interior structure, while he will be assisted in his examination by the accompanying list of names of the most important parts.

CHAPTER V

SOUND

SECTION I

WAVE MOTION

146. Waves. — This word recalls a class of phenomena with which every person is familiar. Every one has watched with interest trains of ridges and furrows traversing the surface of a pond when disturbed by the wind. Every one has seen a wave run along a clothesline when struck with a walking-stick. The student will do well in commencing the study of this subject to attach one end of a cord to some fixed object,



FIG. 116

hold the other end in his hand, stretch the cord horizontally and, by quick and periodical movements of the hand up and down, produce in the cord a train of waves. He will observe (1) that a wave originates in a disturbance at some point in the medium; (2) that this disturbance consists of a vibratory motion, caused by the up-and-down movement of the hand; (3) that the disturbance is propagated successively to other points in the medium; (4) that any particular point in the cord,

e.g., *a* (Fig. 116), simply executes a vibratory motion corresponding to that of the hand, for example in the line *ab*. Hence, we conclude that *wave motion is due to the propagation of vibratory motion to successive points in some medium*.

It will be observed further that while the wave traverses the medium, the medium itself is not transferred. The ocean's billows cause the ship to rise and sink, but do not bear it onward. While, however, there is no transfer of matter, as in the flow of a river, there is a transfer of energy; for there must be a transfer of energy wherever there is a transfer of motion. We have then arrived at a new method by which energy may be transferred, that is, by wave motion.

147. Vibration Frequency; Amplitude; Wave Length.—

By one vibration of a particle we shall understand the motion of the particle from one extreme position to the other *and back again*. The time required to make a single vibration is called the *period* of vibration. The number of vibrations that occur per second is called the *vibration frequency*.

Imagine an instantaneous photograph taken of a cord along which continu-

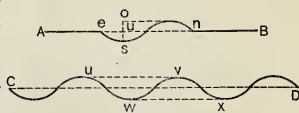


FIG. 117

ous waves are passing. It would appear much like the curved line *CD* (Fig. 117). This curved line represents what is known as a *simple wave line*. The distance from any vibrating point to the nearest point which is at exactly the same stage of its vibration is called a

wave length, as wx , uv , or en . The distance between the extreme positions of a vibrating point or the length of its journey, os , is called the *amplitude of vibration* or the *amplitude of the wave*.

· **148. Waves of Compression and Rarefaction.** — Every wave consists of two parts which are the exact opposites of each other in their character, called its *phases*. For example, a water wave consists of an elevation and a depression. In the waves which we have thus far studied the vibrations are transverse to the direction in which the wave moves. We are now to consider a class of waves whose phases consist of *condensations* or *compressions* and *rarefactions* in some medium, waves in which

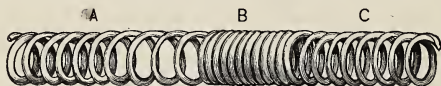


FIG. 118

the vibratory motion is in the direction in which the wave moves. Such vibrations are called *longitudinal vibrations*.

Instead of a cord spoken of above, suppose we use a long spiral spring made of elastic wire. Hold one end of the spiral in one hand and with the thumb nail of the other hand rake it quickly for a short distance lengthwise. We thus crowd close together for a little distance, B (Fig. 118), the turns of wire in front of the hand and leave the turns behind, A , pulled wider apart. The crowded part, B , represents a condensation (or compression) and the stretched part, A , represents a rarefaction, and the two parts collectively represent the two

opposite phases of a wave. This wave, with its condensation in advance followed by its rarefaction, runs with great velocity along the spiral and produces a sharp thump on the object to which it is attached at the other end, and thus transmits energy, through the agency of wave motion, from the hand to the object. Fig. 118 represents a portion of the spiral while it is traversed by a train of waves. *A* and *B* represent an entire wave, while *C* represents the normal condition of the coil.

Waves cannot be transmitted through a spiral made of inelastic soft wire, for the turns after being pulled apart would not close up again. *Elasticity is essential in a medium in order that it may transmit waves of compression and rarefaction; and the greater its elasticity, the greater the facility and rapidity with which a medium transmits waves.*

149. Air as a Medium of Wave Motion. — Being highly elastic, air is a very suitable medium for the transmission of waves. This may be illustrated in an interesting manner as follows:

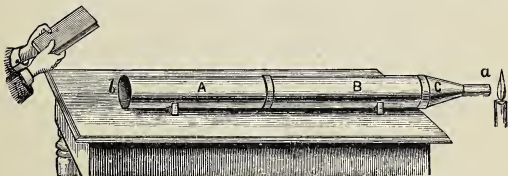


FIG. 119

Place on a table a long tin tube, *AB* (Fig. 119), and at its orifice, *a*, a candle flame. Also hold a smoking paper for a few seconds just inside the end *b* so as to fill this end with smoke. Then strike the table a sharp blow with a book close to the end *b*.

Instantly the candle flame is quenched, but no smoke issues from the orifice *a*. The air in the tube serves as a medium for transmission of motion to the flame. But the motion is not that of a wind, for if it were the smoke that fills the end *b* would be carried along with it. The flame is quenched by a *pulse* in the air and not by a bodily movement of air. If air particles were visible and we could watch the body of air within the tube as it is traversed by the pulse or wave, we should see every particle execute, when the wave reaches it, a single complete short vibration like that of a pendulum bob. Each vibration is in the line in which the wave is moving. As a result of groups of particles executing these vibrations we should see a condensation followed by a rarefaction traversing the tube.

Evidences of the transmission of energy by waves in air are not lacking in our experience. When a great explosion occurs window glass in the neighborhood is frequently broken.

SECTION II

SOUND WAVES

150. Origin and Transmission of Sound. — Of the multitudinous sounds which we hear during a day there are very few which we are unable to trace to their origin; and when we reach the origin of any sound we invariably find ourselves standing in the presence of a *vibrating body*. Be it a bell, a drumhead, a piano string, or the tongue of a boy's jew's-harp, while it sounds it vibrates, and when vibration ceases sound ceases.

We hear at a distance a sounding church bell. How can a bell sounding at a distance affect the ear? A sounding bell possesses no peculiar property except vibratory motion; then it has nothing to communicate

to the ear but motion. But motion can be communicated only through some medium. That air is a medium for conveying sound may be shown by placing a bell struck by clockwork under the receiver of an air pump and exhausting the air. As the exhaustion proceeds the sound becomes more and more feeble.

151. Sound and Sound Waves defined.—As commonly used, the term *sound* is ambiguous, being applied to both a sensation and the physical cause of the sensation. With sound as a sensation we have little to do, as this is a physiological rather than a physical phenomenon. No more appropriate name than *sound wave* can be applied to the physical agent with which we are to deal; it suggests at once the reality, and is not suggestive of some vague mysterious “thing” shot through space.

Sound is a sensation peculiar to the auditory nerves, caused usually by air waves beating upon the organ of hearing.

Sound waves are waves in any medium (usually air) that are capable of producing the sensation of sound.

If we could see the air as it is traversed by sound waves, we should see spherical shells of condensed air alternating with shells of rarefied air, a section of which is roughly represented in Fig. 120. The condensed portions correspond to localities of greater pressure, the rarefied portions to localities of less pressure. When there is an increase of pressure on the drumhead of the ear it is pushed in, and when the pressure becomes less the drumhead springs back.

A body vibrating in an elastic medium, *e.g.*, in air, does not necessarily produce sound waves; in other words, not all waves are sound waves. For example, the energy of the vibrations may

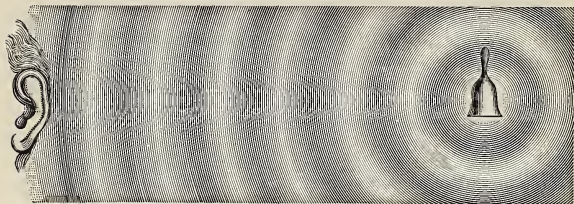


FIG. 150

be insufficient, or the vibrating body may be so small (or the medium so rare), that it cuts through the medium without condensing it sufficiently to produce audible effects.

152. Solids and Liquids are Capable of transmitting Sound Waves. — This may be easily proved by the following experiments:

Experiment 1. — Place one end of a long pole on a cigar box and apply the stem of a vibrating tuning fork to the other end. The sound vibrations will be transmitted through the pole to the box, and a sound will be given out by the box as though that, and not the tuning fork, were the origin of the sound.

Experiment 2. — Place the ear to the earth and listen to the rumbling of a distant carriage; or put the ear to one end of a long stick of timber and let some one gently scratch the other end with a pin.

A diver can hear the voices of people in the air above him. Fishes hear sounds. In the "lover's telephone" sound waves are transmitted from mouthpiece to ear piece along a string or wire. Sound waves lose much of their energy on changing mediums; for example, in passing from air in a room through a solid partition into air in another room.

153. Reflection of Sound Waves; Echoes. — When sound waves meet an obstacle, as for instance the wall of a building, the side of a hill, or even a dense forest, they are reflected, and the sound resulting from the reflected sound waves is called an *echo*. A person must be at least 100 feet from the surface that reflects the sound waves in order to hear an echo of his voice. This is because sufficient time (about $\frac{1}{5}$ of a second) must elapse in the traveling of the sound waves to and from the object for the ear to be able to distinguish between the original sound and its echo. In large halls sound waves are reflected from wall to wall back and forth many times, making it difficult to hear distinctly a speaker's words. This may be remedied in a measure by hanging curtains or tapestry on the walls in such a way that they are poor reflectors of sound waves. Speaking trumpets, ear trumpets, and stethoscopes are so constructed as to concentrate sound waves by reflection.

The laws of reflection of sound and light are the same, and will be fully discussed in the chapter on Light.

SECTION III

VELOCITY OF SOUND WAVES

154. Velocity of Sound Waves dependent on Elasticity and Density of the Medium. — A locomotive whistles at a distance of a mile; an observer sees the jet of steam and after about five seconds hears the shriek of the whistle. From the data given he is able to compute the velocity with which sound waves travel in air. He

sees a lightning flash and counts the seconds before he hears the thunder; and having ascertained the velocity with which sound waves travel in air, he can compute the distance to the source of the sound.

From the general theory of wave propagation it has been clearly demonstrated that the speed of sound waves in a gas bears a simple relation to the elasticity and to the density of the gas. The relation of these quantities is shown in the formula

$$V \propto \sqrt{\frac{e}{d}},$$

in which e and d represent, respectively, the elasticity and the density of the gas, and V the velocity of the sound wave. The interpretation of this formula is that the velocity of a sound wave in a gas varies directly as the square root of its elasticity and inversely as the square root of its density.

If the elasticity and the density of the gas vary in the same ratio, it is evident that the velocity of the sound wave is unaffected. Hence, the velocity of a sound wave is not affected by barometric height, or elevation above sea level. Elevation of the temperature of the air increases its elasticity and therefore tends to increase the speed of the sound wave. The velocity of sound waves in air at 0°C . is about 332 m. (about 1090 feet) per second. The increase of velocity per degree centigrade is about 0.6 m. (about 23.5 inches) per second.

The velocity of a sound wave is greatest in the direction of the wind. Velocity of sound waves is very nearly independent of pitch and intensity. Sound waves, as a rule, travel faster in liquids and solids than in gases owing to greater elasticity of these mediums in proportion to their density. For example, sound waves travel in water about four times as fast as in air,¹ and in iron and in glass sixteen times as fast.

¹ By an experiment performed in Lake Geneva it was ascertained that the velocity of sound in water at a temperature of 8°C . is 1435 m. per second.

EXERCISES

1. The interval of time between seeing a lightning flash and hearing the thunder is 3 seconds. How far away is the thunder cloud (expressed in meters), the temperature of the air being $20^{\circ}\text{C}.$?

2. The flash of light produced by the discharge of a gun is seen across a lake 2 miles wide and the report is heard 9 seconds afterwards. With what velocity (expressed in feet per second) did the sound travel?

3. An echo of one's voice produced by a distant hillside is heard in 5 seconds when the temperature of the air is $0^{\circ}\text{C}.$ How far distant is the hillside, expressed in feet?

SECTION IV

ENERGY OF SOUND WAVES — LOUDNESS OF SOUND

155. **Energy of Sound Waves depends on the Amplitude of Vibration.** — Fix your attention upon a particle of air as a sound wave passes it. At a certain point of its vibratory excursion its velocity is at its maximum. Now, since the energy of a moving particle varies as the square of its velocity, the *intensity* of the impact which it is capable of producing upon the ear is *proportional to the square of this maximum velocity*.

It can be easily proved that if the amplitude of vibration of a particle be doubled while its period remains constant, its maximum velocity is doubled, and therefore its energy is increased fourfold. Hence, (1) measured mechanically the energy of a sound wave is proportional to the square of the amplitude of the vibration of particles, or, it is proportional to the square of the maximum velocity of the vibrating particles.

Loudness of sound refers to the intensity of a sensation. As we have no standard of measurement for a sensation, we are compelled to measure the energy of the sound wave, knowing at the same time that *loudness is probably not proportional to this energy*.

156. Energy of Sound Waves depends upon the Density of the Medium. — Under the receiver of the air pump the sound of a bell becomes feebler as the air becomes rarer. In a rare medium a vibrating body sets in motion fewer particles; consequently, it parts with its energy more slowly and the sound is weaker. Aëronauts are obliged to exert themselves more to make their conversation heard when they reach great heights than when in the denser lower air. On the other hand, in the condensed air of diving bells persons are obliged to speak softly lest the sound of their voices be painfully loud.

(2) The energy of gaseous sound waves increases with the density of the medium in which they are produced.

157. Energy of Sound Waves depends on Distance from their Source. — It is a matter of everyday observation that the loudness of a sound diminishes very rapidly as the distance from the source of the waves to the ear increases. As a sound wave advances in an ever-widening sphere, a given quantity of energy becomes distributed over an ever-increasing surface; and as a greater number of particles partake of the motion, the individual particles receive proportionally less energy; hence, it follows — as a consequence of the geometrical truth that “the surface of a sphere varies as the square of its radius” — that (3) the energy of a sound

wave varies inversely as the square of the distance from the source. The above-mentioned geometrical law is known as the *Law of Inverse Squares*, and is applicable to many other classes of physical phenomena besides those of sound.

158. Speaking Tubes.

Experiment. — Place a watch at one end of the long tin tube (Fig. 119) and the ear at the other end. The ticking sounds very loud, as though the watch were close to the ear.

Long tin tubes, called *speaking tubes*, passing through many apartments in a building, enable persons at the distant extremities to carry on conversation in a low tone of voice, while persons in the various rooms through which the tube passes hear little or nothing. The reason is that the sound waves which enter the tube are prevented from expanding, so that the energy of the sound waves is not affected by distance except as it is wasted by friction of the air against the sides of the tube and by internal friction due to the viscosity of the air.

SECTION V

REËNFORCEMENT OF SOUND WAVES — SYMPATHETIC VIBRATIONS

159. Reënförceiment of Sound Waves.

Experiment 1. — Set a tuning fork in vibration; unless it is held near the ear, you can scarcely hear the sound. Press the stem against a table; the sound rings out loud enough to be heard in all parts of the room, but the sound seems to proceed from the table.

When only the fork vibrates, the prongs, presenting little surface, cut their way through the air, producing

very slight condensations, and consequently waves of little intensity. When the fork rests upon the table the vibrations are communicated to the table; the table with its larger surface throws a larger mass of air into vibration, and thus greatly intensifies the sound waves. The strings of the piano, guitar, and violin owe as much of their loudness of sound to their elastic sounding-boards as the fork does to the table.

160. Reënforcement by Bodies of Air ; Resonators.

Experiment 2.—Take a glass tube, *A* (Fig. 121), 16 inches long and about 2 inches in diameter; thrust one end into a vessel of water, *C*, and hold over the other end a vibrating fork, *B*, that makes, say, 256 vibrations in a second. Gradually lower the tube into the water, and when it reaches a certain depth, *i.e.*, when the column of air *oc* attains a certain length, the sound becomes very loud; as the tube is lowered below this point, the sound rapidly dies away.

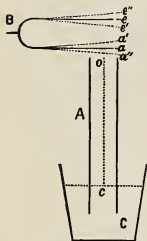


FIG. 121

Columns of air, as well as sounding-boards, serve to *reënforce* sound waves.

The instruments together with the columns of air which they inclose are called *resonators*. Unlike sounding-boards, they can respond loudly to only one tone, or to a few tones of widely different pitch.

How is this reënforcement effected? When the prong *a* moves from one extremity of its arc, *a'*, to the other, *a''*, it sends a condensation down the tube. This condensation, striking the surface of the water, is reflected by it up the tube. Now suppose that the front of this

reflected condensation reaches the prong just at the instant it is starting on its retreat from a'' to a' ; then the reflected condensation will combine with the condensation formed by the prong in its retreat to make a greater condensation in the air outside the tube. Again, the retreat of the prong from a'' to a' produces in its rear a rarefaction, which also runs down the tube, is reflected, and reaches the prong at the instant it is about to return from a' to a'' . The return of the prong from a' to a'' causes another rarefaction in its rear; these two rarefactions moving in the same direction conspire to produce an intensified rarefaction. The original sound waves thus combine with the reflected to produce resonance; but this can happen only when like phases of the two trains of waves coincide; for if the tube were a quarter of a wave length longer or shorter than it is, condensations and rarefactions would concur and destroy one another.

The loudness of sound of all wind instruments is due to the resonance of the air contained within them. A simple vibratory movement at the mouth or orifice of the instrument, scarcely audible in itself (such as the vibration of a reed in reed pipes), is sufficient to throw the large body of air inclosed in the instrument into vibration, and the sound thus reënforced becomes audible at long distances. The human voice owes much of its tone to the resonating cavities of the mouth and nose.

161. Measuring Wave Lengths and the Velocity of Sound Waves.—It can be shown that if we know the vibration number of a fork, we can find the length of the corresponding sound wave as well as its velocity. Suppose the fork to make 256 vibrations per second; the time of half a vibration is $\frac{1}{512}$ of a second. In this

time a condensation goes from o (Fig. 121) to c and back again. The length of the sound wave is, therefore, four times the distance oc ; and the velocity of the sound wave is this wave length multiplied by 256. Thus, suppose the distance oc to measure 13 inches and the vibration number of the fork to be 256. The wave length is $(13 \text{ inches} \times 4 =)$ about 4.3 feet, and the velocity of sound waves in air is $(4.3 \times 256 =)$ about 1100 feet per second.

It is evident that the three quantities expressed in the formula

$$\text{wave length} = \frac{\text{velocity}}{\text{vibration frequency}}$$

bear such a relation to one another that if any two be known, the remaining quantity can be computed. It will further be observed that *with a given velocity the wave length varies inversely as the number of vibrations; i.e., the greater the number of vibrations per second, the shorter the wave length.*

162. Sympathetic Vibrations.

Experiment 3. — Press down gently one of the keys of a piano so as to raise the damper without making any sound, and then sing loudly into the instrument the corresponding note. The string corresponding to this note will be thrown into vibrations that can be heard for several seconds after the voice ceases. If another note be sung, this string will respond only feebly.

Raise the dampers from all the strings of the piano by pressing the foot on the right-hand pedal, and sing strongly some note into the piano. Although all the strings are free to vibrate, only those will respond loudly that correspond to the note you sing, *i.e.,* those that are capable of making the same number of vibrations per second as are produced by your voice.

The pulses or waves that traverse the air between the vocal organs and the strings, so gentle that only the sensitive organ of the ear can perceive them, become great enough to bend the rigid steel wires when the energy of their blows, dealt at the rate of perhaps 512 in a second, accumulates. The large number of blows makes up for the feebleness of the individual blows. Vibrations produced in this manner are called *sympathetic vibrations*.

Such vibrations sometimes produce serious results. Instances are known where the vibrations of machinery in factories have caused in the walls of the buildings sympathetic vibrations which have shaken down the buildings. Military commanders order their troops to "break step" in crossing bridges, lest the vibrations set up might break the bridges down.

SECTION VI

MUSICAL SOUNDS

163. Distinction between Musical Sounds and Noises. —

A sound is a sensation produced by a shock given to the drum of the ear. This sensation dies away rapidly but not instantaneously. When the shocks follow one another so rapidly that the sensation produced by one is not quite gone before another is caused, the impression transmitted to the brain is that of a continuous sound. Every one is familiar with two classes of continuous sounds, called *musical sounds* and *noises*. A musical sound or note is a continuous, uniform, and pleasing sound, such as is given out by one string of a piano; while a noise is an irregular, fitful succession of shocks

to the ear, such as are produced by a wagon rumbling over cobblestones or by a train of cars on an elevated

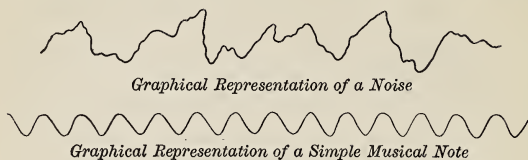


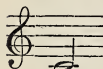
FIG. 122

railroad.¹ Fig. 122 represents graphically the two kinds of sound fairly well.

164. Pitch. — If you draw a finger nail or a card along the teeth of a metallic comb, first slowly and then rapidly, the two sounds produced are commonly described in the former case as *low* or *grave*, and in the latter case as *high* or *acute*. The character of a musical sound as regards gravity or acuteness is called its *pitch*.

Pitch depends upon vibration frequency, or upon wave length; i.e., the greater the number of vibrations per second, or the shorter the wave length, the higher the pitch.

165. Musical Scale. — Suppose a body, *e.g.*, a tuning fork, to make 261 vibrations per second; the sound produced is recognized by our musical sense as the note



which corresponds to the so-called middle C

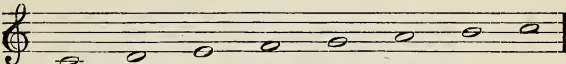
(c') of a piano tuned to the national standard pitch.²

¹ The sensation of a musical tone is due to a rapid periodic motion of a sonorous body; the sensation of a noise to a non-periodic motion. — HELMHOLTZ.

² In a convention of piano manufacturers held in New York it was decided that the national pitch, to go into effect July 1, 1892, should be the standard French, Austrian, and Italian pitch of 261 vibrations for middle C.

The pitch of a sound produced by twice as many vibrations as that of another sound is called the *octave* of the latter. Between two such sounds the voice rises or falls, in a manner very pleasing to the ear, by a definite number of steps called *musical intervals*. This gives rise to the so-called *diatonic scale*, or *gamut*. The interval between two notes is the ratio of their frequencies. The vibration number which shall constitute a given note is purely arbitrary, and differs slightly in different countries; but the ratios between the vibration numbers of the several notes of the gamut and the vibration number of the first or fundamental note of the gamut are the same among all enlightened nations.

The interval between each note in the scale and the fundamental (1), the interval between each two consecutive notes (2), and two series of whole numbers which are proportional to the frequencies (3) are shown in the following table:

								
	c'	d'	e'	f'	g'	a'	b'	c''
(1)	1	$\frac{9}{8}$	$\frac{5}{4}$	$\frac{4}{3}$	$\frac{3}{2}$	$\frac{5}{3}$	$\frac{15}{8}$	2
(2)		$\frac{9}{8}$	$\frac{10}{9}$	$\frac{16}{15}$	$\frac{9}{8}$	$\frac{10}{9}$	$\frac{9}{8}$	$\frac{16}{15}$
(3)	24	27	30	32	36	40	45	48
or	261	293.62	326.25	348	391.5	435	489.37	522

The ear is incapable of determining the number of vibrations corresponding to a given tone, but often it is capable of determining with wondrous precision the *ratio* of the vibration numbers of two notes; hence, all music must depend upon the recognition of such ratios, and in considering the relations between the pitches of musical notes, we have to deal with ratios of their frequencies, and not with differences of vibration numbers.

SECTION VII

COMPOSITION OF SONOROUS VIBRATIONS AND THEIR
RESULTANT WAVE FORMS

166. Coexistence and Superposition of Waves; Interference. — When two or more currents of waves traverse the same medium at the same time and in the same or opposite directions, so that one set of waves is, as it were, superposed upon another, all the vibratory motions peculiar to the several waves are imparted to every particle of the medium simultaneously, and the actual motion of a particle is the *resultant* of the several motions combined.

This will be best understood by means of a graphical representation. The light lines in *AB* (Fig. 123) represent the wave

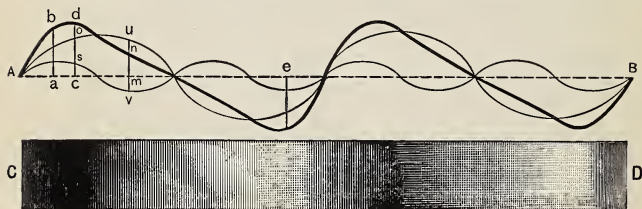


FIG. 123

lines of two coexisting currents of waves originating at *A*. The heavy line represents the *form* which the joint wave takes resulting from the combination of the two. The wave lengths of the two components are as 2:1, *i.e.*, there is an octave difference in their pitches. If we draw lines perpendicular to the dotted line, or line of repose, as *ab*, *cd*, *mn*, etc., to represent the amplitudes of the resultant vibrations of particles at these points at a

given instant, it will be found that these amplitudes are the algebraic sum of the amplitudes of the corresponding component vibrations. For example, $cd = cs + co$, and $mn = -mv + mu$.

In diagrams, for obvious reasons, it is much easier to represent transverse vibrations with the understanding that the results depicted apply equally well to longitudinal vibrations and to waves of condensation and rarefaction. The rectangular diagram CD is intended to represent a portion of a transverse section of a body of air traversed by the joint wave corresponding to the heavy wave line above. The depth of shading in different parts indicates the degree of condensation or rarefaction at those parts.

It will be observed from the diagram that the pitch of the resultant is the pitch of the graver of the two sounds. It is called the *fundamental* tone.

167. Interference.

Experiment.—Hold a vibrating fork over a resonance jar, as in Fig. 124. Rotate the fork slowly in the fingers. At certain points about a quarter of a revolution apart, when the fork is in an oblique position as represented in the figure, the reinforcement from the tube almost entirely disappears, but it reappears at the intermediate points. That is, when the fork is in the position shown in the figure one prong tends to send a condensation into the jar at the same time that the other prong tends to send a rarefaction, and this results in a mutual destruction. Return to the position where there is no resonance, and, without touching

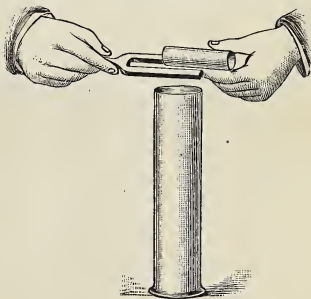


FIG. 124

the fork, inclose in a loose roll of paper the prong farthest from the tube, so as to prevent the sound waves produced by that prong from passing into the tube; the resonance resulting from the vibrations of the other prong immediately appears.

Two sound waves may combine to produce a sound louder or weaker than either alone would produce, or even to cause silence. This combination of sound waves to produce a louder or weaker sound is called *interference*.

SECTION VIII

VIBRATION OF STRINGS

168. Sonometer.—This instrument consists of two or more piano wires of different thicknesses stretched lengthwise over a resonance box. One end of each wire is attached to the shorter arm of a bent lever, *A* or *B* (Fig. 125), and the tension of the wire is regulated both

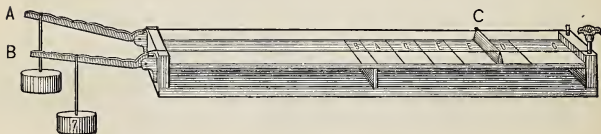


FIG. 125

by the lengths of the longer arms employed and by the magnitude of the weights suspended therefrom. The length of the vibrating portion of the strings is regulated by the sliding bridge *C*.

By a series of experiments with this apparatus the following relations are obtained:

The times of vibration of stretched strings of the same material vary :

- (1) Directly as the length of the strings.
- (2) Directly as the square root of their masses per unit of length.
- (3) Inversely as the square root of their tensions.

We will take for illustration the guitar as a typical stringed instrument. It has six strings, three of silk covered with silver wire, and three of catgut. Its range is about three octaves. The pitch in this instrument is varied in three ways: (1) Screws are employed to vary the tension of the strings. (2) To pass from one note to another on the same string, the finger presses the string down on a "fret" and thus changes the length of the string. (3) The pitch of the lower strings is diminished by increasing their masses. This is accomplished by having them wound with fine silver wire.

In the piano the pitch of a string depends on its length, mass, and tension. It is not intended that the tension of any one string shall change. If from any cause the tension changes, the piano is said to be "out of tune."

169. Beats.

Experiment 1.—Strike simultaneously the lowest note of a piano and its sharp (black key next above) and listen to the resulting sound.

You hear a peculiar wavy or throbbing sound, caused by an alternate rising and sinking in loudness. These variations of intensity are called *beats*.

Let the continuous curved line AC (Fig. 126) represent a wave proceeding from the lower key, and the dotted line one from the upper key. Now the waves from both keys may start together at A ; as the wave from the lower key has a greater wave length, at certain

intervals, as at *B*, condensations will correspond with rarefactions, producing by their interference momentary silence, too short, however, to be perceived; the sound

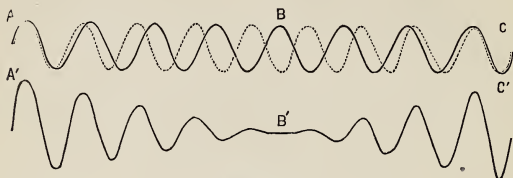


FIG. 126

as perceived by the ear is correctly represented in its varying loudness by the curved line *A'B'C'*.

It will be apparent from the study of Fig. 126 that the number of beats is equal to the difference of the vibration numbers of the two tones. *The number of beats per second due to any two simple tones is equal to the difference of their respective vibration numbers.*

170. Stationary Waves; Harmonics. — If you put a finger exactly one third along from one end of a string of a sonometer so as to “damp” it (*i.e.*, quench its vibrations) at that point, and bow this third of the string, the note produced is a twelfth above the note given by the open string. That is, should the open string give the note *C*, the same string in this case will give *G'*. If some little paper riders be placed at intervals along the string, it will be found that the string vibrates in these sections as shown in (3), Fig. 127, for the riders will be thrown off except at the points of trisection. By damping the string one half and one fourth its length from

one end, as in (2) and (4), the notes given will be C' and C'' , respectively, and the vibration frequencies of the

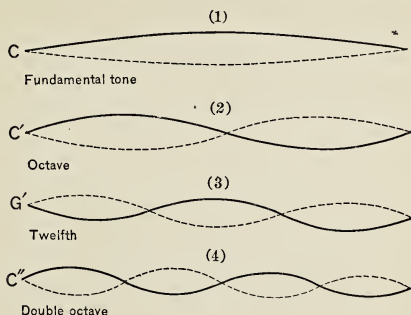


FIG. 127

several sections will be, as we should expect, twice and four times that of the open string.

The points at which there are no vibrations are called *nodes*, and the portions between the nodes are called *anti-nodes*. The waves are called *stationary waves* because they do not appear to advance like waves along a cord when shaken at one end. The note given by the open string is called the *fundamental tone*, and the others are called its *harmonics* or *upper partial tones*.

171. Complex Vibrations.

Experiment 2.—Press down the C' key of a piano gently, so that it will not sound, and while holding it down strike the C key strongly. In a few seconds release the latter key, so that its damper will stop the vibrations of the string that was struck, and you will hear a sound which you will recognize by its pitch as coming from the C' wire. Place your finger lightly on the C' wire and you will find that it is indeed vibrating. Press down the

right pedal with the foot, so as to lift the dampers from all the wires, strike the C key, and touch with the finger the C' wire; it vibrates. Touch the wires next to C', viz., B and D'; they have only a slight forced vibration. Touch G'; it vibrates.

It is evident that the vibrations of the C' and G' wires are sympathetic. Now a C wire vibrating as a whole cannot cause sympathetic vibrations in a C' wire; but if it vibrates in halves, it may. Hence, we conclude that when the C wire was struck it vibrated, not only as a whole, giving a sound of its own pitch, but also in halves; and the result of this latter set of vibrations was that an additional sound was produced by this wire, just an octave higher than the first-mentioned sound.

It thus appears that a string may at the same time vibrate as a whole and in halves, thirds, etc., and the result is that *a sensation is produced that is compounded of the sensations of several sounds of different pitch*. A sound so simple that it cannot be resolved is called a *tone*. A sound composed of many tones is called a *note*.

No musical instrument is capable of producing a *simple tone*, i.e., a sound generated by vibrations of a single period. In other words, *when any note of any musical instrument is sounded there is produced, in addition to the primary tone, a number of other tones in a progressive series, each tone of the series being usually of less intensity than the preceding*.

172. Discord and Harmony.—When two or more musical sounds are produced at the same time the effect on the ear, if disagreeable, is called *discord*; if agreeable, it is called *harmony*.

Helmholtz proved that discord is due to *beats*, and that discord is most harsh when the number of beats produced by two simultaneous sounds is from thirty to forty per second. As the number becomes greater than this, the ear begins to lose its perception of the alternations in the sound, which, therefore, becomes to the ear more and more continuous. The effect of beats on the ear is analogous to that of a flickering light on the eye. Both are disagreeable. But if the beats are very rapid, they coalesce and cease to be disagreeable, much as the electric light alternating in intensity ceases to be painful when the alternations are very rapid.

It is easy to see why tones whose vibration frequencies bear simple ratios to each other, such as $1 : 2$, $2 : 3$, $3 : 4$, etc., should harmonize when sounded together. Take, for instance, the middle C of a piano and its octave above it. Their frequencies are as $261 : 522$, or as $1 : 2$, so that the two sets of waves coincide 261 times every second. It is also apparent why the voices of men and women easily harmonize when they sing together, since the voices of the latter are usually an octave higher than the former. The laws of harmony are very intricate, but it may be stated in general that in order that two notes may harmonize, the vibration numbers of their fundamental tones must bear to each other ratios expressed by small numbers (*e.g.*, $1 : 2$, $2 : 3$, etc.), and the smaller these numbers, the more pleasing the harmony.

The highest expression of musical art is in harmony, which is the combining of many sounds into one agreeable composition.

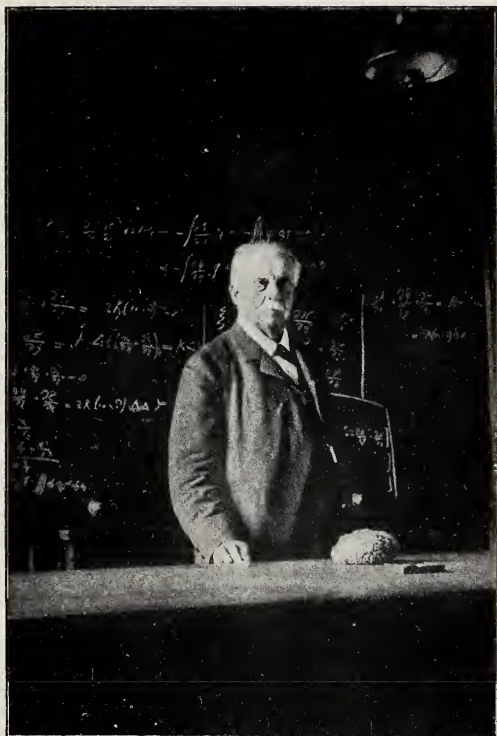
SECTION IX

QUALITY OF SOUND

173. Complex Sound Waves. — Simple sound waves can differ only in length and amplitude; consequently, the sounds which they produce can differ only in pitch and loudness. Complex sound waves may differ, as we have seen (§ 166), in *form*, and this gives rise to a property of sound called *quality*. Quality is that property of sound, not due to pitch or intensity, that enables us to distinguish one sound from another. It is that property that enables us to distinguish the voices of our friends when our back is turned to them, and to distinguish the sounds of different instruments in an orchestra. The most remarkable property of the ear is its ability to distinguish sounds of different qualities.

Although the variety of sounds one hears appears well-nigh infinite, yet no two sounds can differ from each other in any other respect than in *pitch*, *loudness*, and *quality*. The length, amplitude, and form of the wave completely determine it. Loudness depends on the *amplitude* of the wave, pitch on its length, and quality, as Helmholtz proved, on the *upper partial tones* which accompany the fundamental tone, *i.e.*, on *wave form*. The following classification will assist the pupil in associating the several particulars :

THE VIBRATING BODY HAS	THE WAVE HAS	THE SOUND HAS
<i>frequency</i>	<i>wave length</i>	<i>pitch</i>
<i>amplitude</i>	<i>amplitude</i>	<i>intensity</i>
<i>complexity</i>	<i>form</i>	<i>quality</i>



HERMANN VON HELMHOLTZ (1821-1894)

Distinguished for his researches in physiology and physics, more especially in the departments of acoustics and physiological optics. After a photograph by a student.

Helmholtz analyzed sounds of different musical instruments by means of a set of resonators (one of which is represented in Fig. 128) corresponding to the various tones used in music. By applying one resonator after another to the ear he was able to detect the component tones of sounds far too complex to be analyzed by the unaided ear.

Musical instruments are of little value unless their tones are rich in upper partials. The human voice in general is especially well supplied in this respect, but "O what a difference between the voice of a Patti and that of the average uncultivated savage!"

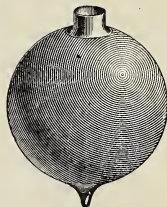


FIG. 128

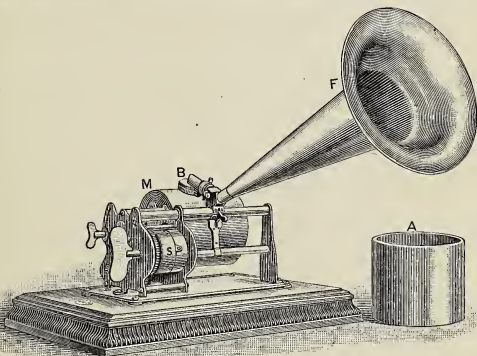


FIG. 129

174. The Phonograph. — This instrument is designed to reproduce human speech. It is constructed on the principle that as sound is produced by vibrations of air, any sound can be reproduced

by reproducing these vibrations. A hollow cylinder of wax, *A* (Fig. 129), is slipped over the metallic cylinder *M*. The mouthpiece *B* (better shown in Fig. 130) is next placed in position. Closing the small end of the mouthpiece is an extremely thin disk of glass, *C* (Fig. 130), to which a graving point, *D*, is attached.

Now when a person directs his voice toward the mouthpiece, the aerial waves cause the disk *C* to participate in every motion of the air, and this vibratory motion of the disk causes the point *D* to indent the wax. The cylinder *M* meanwhile is kept rotating uniformly by means of a spring and clock-work, *S*, and at the same time the cylinder moves slowly lengthwise. When the disk is at rest the point traces on the wax cylinder

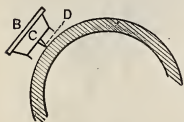


FIG. 130

a spiral groove of uniform depth. But when the disk is caused to vibrate, the groove becomes of variable depth, corresponding to the rarefactions and compressions of the air. This groove thus forms a permanent record of the vibrations of the disk.

To reproduce the sound, another more delicate point attached to a similar disk is made to work in the same groove, so that when the cylinder is rotated, the point on the second disk passes over the elevations and depressions in the groove and is thus made to vibrate in the same way as did the recording point. This motion is communicated to the disk, causing it to vibrate in the same manner as it did under the influence of the incident sound waves. The disk communicates its motion to the air, and thus the sounds are reproduced. The office of the resonator *F* is to give direction to the sound waves and to render them audible.

While, commercially considered, the phonograph is little more than a toy, yet from a scientific standpoint it illustrates in a very comprehensive manner the entire mechanism of sound. It also represents the only completely successful attempt to reproduce human speech artificially. Words spoken to the instrument to-day may be reproduced with the identical intonations and qualities of sound in the hearing of any succeeding generation.

SECTION X

PRODUCTION OF VOCAL SOUNDS — AUDITION

175. Production of Vocal Sounds. — The actual organ for the production of vocal sound waves consists of two elastic membranes, *aa* (Fig. 131), called the *vocal cords*. These cords are stretched across the top of the windpipe, which is a tube leading to the lungs, and it is to the vibrations caused in the cords when air from the lungs is forced through the slit-like opening *b* between them that vocal sounds are due. The length and tension of these vocal cords can be altered by muscular action with great rapidity; hence, the extreme flexibility and great range of tone, usually called *compass*, of the human voice. The vocal cords in men are thicker than in women and children, so that they vibrate more slowly, and therefore produce lower tones.

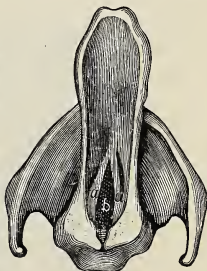


FIG. 131

The sounds produced by the vocal cords are greatly modified by varying the shape of the resonance cavity of the mouth. It is easy for one to find out for oneself, by uttering the four sounds of the vowel *a* one after another, that the altering of the shape of the mouth produces the change of vowel sound. This is *articulation*.

176. Audition. — Sound waves enter the ear passage *C* (Fig. 132), and, beating against the thin membrane *D* known as the *eardrum*, impress upon it the precise wave forms that are transmitted to it from the sounding body. This wave motion is transmitted to the chambers *OO* of the inner ear, which are filled with a liquid. Into this liquid from the walls of these chambers project thousands of stiff elastic hairs of varying length and size. The auditory nerve *TT* is divided at this extremity into filaments,

one of which is attached to each hair. When the wave motion reaches the liquid contents of the inner ear the hairs immersed therein receive the impulses.

Now if you raise all the dampers off the strings of a piano by pressing down the right-hand pedal, and sing strongly the vowel sounds *ah*, *oo*, and *ee*, for instance, against the sounding-board, stopping to listen to the response, there will be given back by the

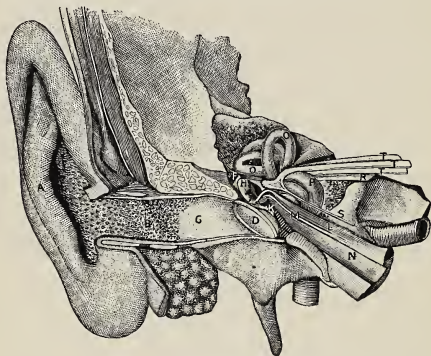


FIG. 132

wires a surprisingly perfect *ah*, *oo*, *ee*, etc. Each wire selects the particular constituent of the sound with which it is in sympathy, and the compound tone given back is an almost perfect duplicate of the original.

In a similar manner we suppose the different hairs to act like the piano wires, and each to select that particular ripple in the big wave with which it is in sympathy. The nerve filaments connected therewith transmit the impression to the brain, where in some mysterious manner these disturbances are interpreted as sound of definite *pitch*, *quality*, and *loudness*.

177. Limits of Audibility, etc. — There is a limit to the pitch which is audible to the human ear. The following list of approximate values of corresponding vibration frequency is submitted:

AIR VIBRATIONS PER SECOND

Range of human hearing	{	40,000	highest audible sound.
		30,000	the shrill cry of a bat.
		4,000	highest musical note used.
		2,000	high soprano note.
		512	
		to	woman's conversational voice.
		256	
		128	man's voice (conversational).
		32	lowest musical note used.
		16	lowest audible sound.

REVIEW EXERCISES

1. On what two things does the length of sound waves depend?
2. The energy of sound waves diminishes as they advance. What change in the vibration of the particles of the medium occurs?
3. State, respectively, the three properties of a sound wave that determine the three properties of a sound sensation, *viz.*, *pitch*, *intensity*, and *quality*.
4. What is the length of sound waves in feet, propagated through the air at a temperature of 20° C. by a tuning fork that vibrates 256 times per second?
5. What is the vibration number of the tone *g''* of an American piano?
6. If two tuning forks, vibrating respectively 256 and 258 times per second, are sounded simultaneously, what phenomenon will occur?
7. If a tube 30 cm. long, closed at one end, responds most loudly to a certain fork, what is the length of the sound waves produced by the fork?
8. A string 30 inches long produces the tone *c'*. Must it be lengthened or shortened to produce *g'*, and in what ratio?
9. The tension of a sonometer string is 9 pounds. What should be its tension that its pitch may be lowered an octave?
10. When a bottle of soda water is opened a sound is heard. Explain.
11. Which is the better conductor of sound, sawdust or solid wood? Why?

CHAPTER VI

RADIANT ENERGY — LIGHT

SECTION I

RADIANT ENERGY

178. Ambiguity in the Use of the Term Light. — To any one not born blind the word *light* conveys a definite meaning. It is a *sensation* perceived by means of the eye ; but, like the word *sound*, it is commonly applied to that which produces the sensation. It was in the latter sense that the word *light* was used in that primeval injunction, “ Let there be light,” for “ in the beginning ” there was no material eye to receive an impression.

179. Theory of Light ; the Ether. — Two widely different theories regarding the nature of light have been propounded. One, the so-called *emission* or *corpuscular theory*, was supported by Newton (1672), and by most physicists up to the early part of the nineteenth century. It assumes that a luminous body (*e.g.*, the sun, a candle flame) emits streams of minute material particles (corpuscles) which travel through space in all directions with immense velocity, and that these particles by their impact upon the retina of the eye produce the sensation of sight.

Since light can traverse not only so-called empty space, but also some forms of matter, *e.g.*, glass, water,

etc., it was necessary to assume that these particles were able to pass between the molecules of matter. This theory has been found incapable of explaining, and in some cases wholly inconsistent with, many phenomena discovered since Newton's time, and it is now discarded by scientists.

The theory which obtains at the present time, called the *undulatory* or *wave theory*, is based upon the hypothesis that energy is transmitted from body to body, *e.g.*, from the sun to the earth, by means of waves through an all-pervading highly elastic medium called *the ether* (§ 1). This medium is assumed to fill all interstellar and all intermolecular space. The ether is as yet very much of a mystery. The evidence that it exists, briefly stated, is that *only on the hypothesis that all space is filled with a medium capable of transmitting energy in the form of wave motion are we able to offer rational explanation for all known optical phenomena.*

According to this theory, *light is that wave motion in the ether which may be appreciated by the eye.*

It will be shown further on that not all ether waves are capable of effecting the sight; hence, for the purpose of distinction, we apply the term *light waves* to those ether waves only which are capable of producing vision.

180. Radiation ; Radiant Energy. — Sound waves are generated in air by mass vibration, such as that of a piano wire or of the prong of a tuning fork. Ether waves are generated in the ether by the vibratory motions of the molecules of matter, whose frequencies are, in general, vastly greater than those of bodies producing sound

waves. By means of ether waves energy is transferred through space from body to body, and in fact a continuous interchange of energy is ever going on between all bodies. The process by which the transfer takes place is called *radiation*, energy thus transferred is called *radiant energy*, and a body thus emitting energy is called a *radiator*. Radiant energy can be transformed into any other form of energy, and therefore offers no exception to the doctrine of correlation of energy. The energy of ether waves on reaching a body is commonly transformed into heat.

181. Effects of Radiant Energy. — When radiant energy is received upon the surfaces of our bodies, warmth may be felt; when received upon the bulb of a thermometer, rise of temperature may be caused; when received by the eye, sight may be effected; when received upon sensitive photographic plates, upon the leaves of plants, or upon various chemical mixtures, chemical changes may be promoted. Thus, it seems that when ether waves impinge upon objects their energy is transformed, producing effects of different kinds, which are determined by the nature of the body upon which they fall. The effect which most concerns us is that produced when the radiations strike the *eye* and become the means, through this organ, of creating the sensation of *sight*.

182. Luminous and Illuminated Objects. — Some bodies are seen by means of light waves which they generate, *e.g.*, the sun, a candle flame, and a “live coal”; they are called *luminous bodies*. Others are seen only by

means of light waves which they receive from luminous bodies and reflect to the eye; they are said to be *illuminated*; examples are the moon, a man, a cloud, and a "dead" coal. You are now reading by light reflected from the paper in this book.

183. Light Waves travel in Straight Lines. — The paths of light waves admitted into a darkened room through a small aperture, as indicated by the illuminated dust, are perfectly straight. *An object is seen by means of light waves which it sends to the eye.* A small object placed in a straight line between the eye and a luminous particle may intercept the light waves in that path, so that the particle becomes invisible. Hence, we cannot see around a corner or through a bent tube. A straight line indicating the direction in which ether waves are propagated is called a *ray*.¹ A collection of rays is called a *beam*, or, in the case of rays proceeding from a point or approaching a point, a *pencil*.

184. Transparent, Translucent, and Opaque Substances. — Substances are *transparent*, *translucent*, or *opaque* according to the manner in which they act upon the light waves which are incident upon them. Generally speaking, those substances are *transparent* that allow objects to be seen through them distinctly, *e.g.*, air, glass, and water. Those substances are *translucent* that allow light waves to pass, but in such a scattered condition that objects are not seen distinctly through them, *e.g.*, fog, ground glass, and oiled paper. Those substances

¹ The word *ray* must be understood to mean nothing more than the geometrical line along which a piece of the wave front moves.

are *opaque* that apparently obstruct all the light waves. In such cases the light waves are said to be *absorbed*. In reality their energy is transformed into heat, and the absorbing body is warmed thereby.

185. Every Particle of a Luminous Body an Independent Source of Light Waves. — Place a candle flame in the

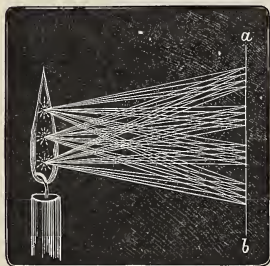


FIG. 133

center of a darkened room. Stand in any part of the room and you are able to see not only the flame but every point of the flame; hence, *every point of a luminous body is an independent source of light waves which are emitted in every direction*. Such a point is called a *luminous point*. In Fig. 133

are represented a few of the infinite number of pencils of light emitted by three luminous particles.

186. Shadows. — Let L (Fig. 134) locate a single luminous particle, ab an opaque body, and cd a screen. Evidently no light from L can enter the space $acdb$. This space is called a *shadow*. A cross section of the shadow, as cd , is frequently for convenience called a *shadow*, and represents in outline a cross section of the body that intercepts the light.

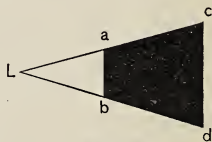


FIG. 134

In Fig. 135, F represents a candle flame, and m and n extreme points of the flame. In this case the shadow consists of two parts, a dark center, $acdb$, called the *umbra*, from which the light is wholly excluded, and a lighter envelope, called the *penumbra*, inclosing the umbra. The penumbra, a section of which is included between ae and ac , and between bf and bd , receives light from portions of the flame but not from the whole flame. The penumbra grows gradually denser from its outer limits toward the umbra, so that it is impossible for the eye to distinguish the boundary surface between the umbra and penumbra.

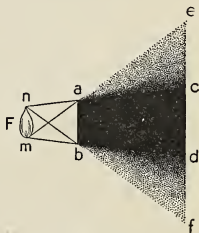


FIG. 135

It is evident that if the luminous body consists of a single luminous particle, as shown in Fig. 134, there can be no penumbra, and that, generally, the smaller the luminous body the less apparent the penumbra becomes and the more distinct the outlines of the umbra. It is on account of its smallness that the so-called "crater" of an electric arc, an intensely brilliant spot of light, casts very sharply defined shadows.

187. Images formed through Small Apertures.—If light waves from objects illuminated by the sun — *e.g.*, trees, houses, clouds, vehicles — be allowed to pass through a small hole and strike a white screen in a dark room, inverted images of the objects in their true colors will appear upon the screen. The reason for these phenomena is easily understood. When no screen intervenes between the candle and the screen, S (Fig. 136),

every point of the screen receives light from every point of the candle; consequently, at every point on S images of all the points of the candle are formed. The result of

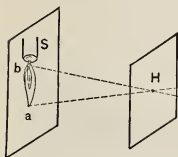


FIG. 136

the confusion of images is that no image is distinguishable. But let the screen H , containing a small hole, be interposed; then, since light travels only in

straight lines, the point a can receive an image only of the point A , the point b only of the point B , and so for intermediate points; hence, a distinct image of the object must be formed on the screen S . *That an image may be distinct, the images of different points of the object must not mix, and therefore rays from each point on the object must be carried only to the corresponding point on the image.*

188. Velocity of Light Waves. — For all distances which we are able to observe on the earth the speed with which light waves travel seems infinite. Hence, the discovery in 1676 by Römer, a Danish astronomer, that the velocity of light is finite was an important contribution to man's knowledge. He made observations on one of Jupiter's satellites, which revolves round that planet as the moon does round the earth. When the satellite passes into the shadow which Jupiter casts in a direction opposite the sun it is eclipsed. But sometimes the earth and Jupiter are on the same side and sometimes on opposite sides of the sun. Let S (Fig. 137)

represent the sun, E the earth, and J Jupiter. Römer discovered that an eclipse of the satellite is seen about 1000 seconds sooner when the earth is nearest to Jupiter than when it is most remote, whence he concluded

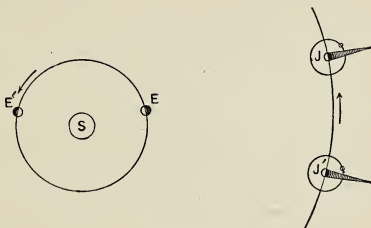


FIG. 137

that this time must be required for the light to travel the difference of path between $J'E'$ and JE , or the diameter of the earth's orbit. Assuming this distance to be 186,000,000 miles, the velocity of light must be about 186,000 miles per second. Various independent methods have been used to determine the velocity of light; suffice it to say they all agree very closely with the velocity as here given. At this rate light waves would go around the earth between seven and eight times in a second, or while sound waves would travel about one fifth of a mile.

EXERCISES

1. Why are images formed through apertures inverted?
2. Why is the size of the image dependent on the distance of the screen from the aperture?
3. Why does an image become dimmer as it becomes larger?

4. Why do we not imprint an image of our person on every object in front of which we stand?
5. Upon what fact does a gunner rely in taking sight?
6. Is a perfectly transparent body visible?
7. At what time in the day is the shadow of an upright stick shortest?
8. What does the great velocity with which light waves travel indicate respecting the elasticity of the ether?
9. Why is it difficult to determine the exact line on the ground where the umbra of a church steeple terminates?
10. What is the shape of a section of the shadow cast by a circular disk placed obliquely between a luminous particle and a screen? What is its shape when the disk is placed edgewise?
11. The section of the earth's umbra on the moon in an eclipse always has a circular outline. What does this show respecting the shape of the earth?
12. (a) The sensation of sound is how produced? (b) How is the sensation of sight produced? (c) How are sound waves produced? (d) How are light waves produced? (e) Which, sound waves or ether waves, originate in molecular vibrations? (f) Sound waves travel in what mediums? (g) Light waves travel only in what medium?
13. (a) What is radiant energy? (b) Do all bodies emit radiant energy? (c) Do all ether waves effect sight? (d) Do all bodies generate light waves? (e) Is a "dead" coal seen by ether waves which it generates?

SECTION II

INTENSITY OF ILLUMINATION

189. Law of Inverse Squares. — Every one knows that a gas flame gives a stronger light than a candle flame. If a sheet of white paper be held midway between these two flames, the side next the candle flame will appear considerably darker by contrast than the side next the gas flame. Indeed, it might require as many as sixteen candle flames to illuminate the paper as much as the

single gas flame, provided the distances from the paper were equal. The power of illumination is determined by the amount of light received by a unit area of illuminated surface. We are aware that the illumination of a given surface diminishes as it recedes from the source of light. The intensity of this illumination diminishes as the square of the distance from its source increases. For example, suppose we assign the value *one* to the illumination of a visiting card when placed at a distance of 1 foot from a lamp flame; then the card will have an intensity of illumination equal to *one fourth* if placed at a distance of 2 feet, *one ninth* if at 3 feet, and so on. This is the Law of Inverse Squares as applied to light.

This law may be illustrated thus: A square card placed 1 foot from a certain point in a candle flame, as at *A* (Fig. 138), receives from this point a certain quantity of light. The same light if not intercepted would go on to *B*, at a distance of 2 feet, and would there illuminate four squares, each of the size of the card, but, being spread over four times the area, can illuminate each square with only one fourth the intensity. If allowed to proceed to *C*, 3 feet distant, it would illuminate nine such squares and would have only one ninth its intensity at *A*.

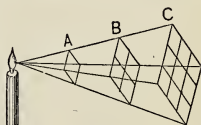


FIG. 138

The unit generally employed in the measurement of the illuminating power of the light emitted by a luminous body is the British *candle-power*. It is the illuminating power of a sperm candle $\frac{1}{8}$ of an inch in diameter, burning 120 grains to the hour.

190. Photometry. — The law given above enables us to compare the illuminating power of one light with that of another, and to express by numbers their relative illuminating powers. The process is called *photometry* (light measuring).

Experiment. — Place an opaque rod, *C* (Fig. 139), vertically a little way in front of a white screen so as to cast shadows, *a* and *b*, of two lights, *A* and *B*, side by side on the screen. The portion

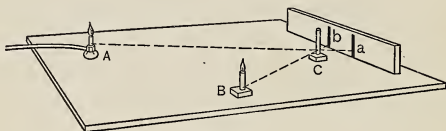


FIG. 139

of the screen upon which the shadow *a* falls receives light only from the candle *B* and none from the gas flame *A*; the portion *b* is illuminated by *A* alone. The rod *C* thus secures for each light a portion of the screen which it alone illuminates. Move either light toward or from the screen until both shadows become equally intense. Then measure the distances from *A* to *b* = *c*, and from *B* to *a* = *d*. *B* at distance *d* illuminates the screen as intensely as *A* at distance *c*. Hence (see § 189),

$$A : B = c^2 : d^2;$$

or, *the intensities vary directly as the squares of those distances from the screen at which equal illumination is obtained.*

EXERCISES

1. (a) Suppose that a lighted candle is placed in the center of each of three cubical rooms, respectively 10, 20, and 30 feet on a side. Compare the intensities of illumination of the walls of the several rooms. (b) Compare the total amount of light received by an entire side of each of the rooms.

2. If a board 10 cm. square be placed 25 cm. from a candle flame, the area of the shadow of the board cast on a screen 75 cm. distant from the candle will be how many times the area of the board? Then the light intercepted by the board will illuminate how much of the surface of the screen if the board be withdrawn?

3. The two sides of a paper disk are illuminated equally by a candle flame 50 cm. distant on one side and a gas flame 200 cm. distant on the other side. (a) Compare the illuminating powers of the two lights at equal distances from their sources. (b) If the candle be a standard candle, what is the intensity of the gas flame?

SECTION III

REFLECTION OF LIGHT

191. Mirrors; Images. — Polished surfaces which reflect light regularly (*i.e.*, do not scatter the light) and show images of objects presented to them are called *mirrors*. The mirror itself, if clean and smooth, is scarcely visible. According to their shape, mirrors are called *plane*, *concave*, *convex*, *spherical*, *parabolic*, etc.

Experiment 1. — Draw a straight line, *L* (Fig. 140), on a large sheet of white paper spread upon a table. Take a rectangular piece of mirror glass, *M*, about 10 cm. by 3.5 cm., and support it vertically on one of its long edges on this line so that the silvered surface is just over this line. At some point, *A*, stick a pin vertically. Place your eye at some point, *E*, so that you can see the image of the pin. Glancing just over the upper edge of the mirror, stick another pin, *A'*, so that it coincides with the image of the first pin.

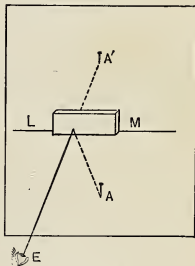


FIG. 140

You are now to verify the following facts:

(1) Looking at the image from different points of view, the image does not change its position. *The image has a fixed position in space independent of the observer.*

(2) But if the object (*i.e.*, the pin) be moved or the mirror be inclined to the line L , the image also moves.

(3) Connecting points A and A' by a straight line, as in Fig. 141, you find this line is perpendicular to the reflecting surface.

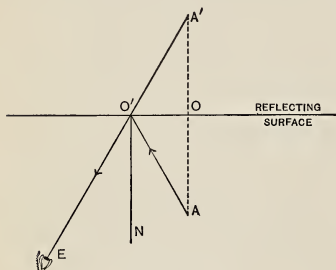


FIG. 141

(4) Measuring the distances AO and $A'O$, you find that the object and its image are at equal distances from the reflecting surface.

Hence, we conclude that the image of a point in a plane mirror lies on the perpendicular let fall from the point to the mirror, and is as far behind the mirror as the point is in front of the mirror.

192. Law of Reflection. — The point A (Fig. 141) emits rays in all directions. Let AO' represent one of those rays. Then the two right-angled triangles $A'O'O$ and $AO'O$ are equal, since they have one common side, and the sides $A'O$ and AO are equal. Hence, the angles $O'AO$ and $O'A'O$ are equal.

Draw the line NO' perpendicular to the mirror at point O' . Then the angles $NO'E$ and $NO'A$ are equal, since they are respectively equal to $O'A'O$ and $O'AO$.

The angle between the normal and the incident ray $AO'N$ is called the *angle of incidence*. The angle between the normal and the reflected ray $NO'E$ is called the *angle of reflection*.

The law of reflection of light may be stated as follows: At every point of a reflecting surface the angle of reflection is equal to the angle of incidence.

193. Diffused Light.

Experiment 2.—Introduce a small beam of sunlight into a darkened room, and place in its path a mirror. The light is reflected in a definite direction. If the eye be placed so as to receive the reflected light, it will see, not the mirror, but the image of the sun, and the light will be painfully intense. Substitute for the mirror a piece of unglazed paper. The light is not reflected by the paper in any definite direction, but is scattered in every direction, illuminating objects in the vicinity and rendering them visible. Looking at the paper, you see, not an image of the sun, but the paper itself, and you may see it equally well from all directions.

The surface of the paper receives light from a definite direction, but reflects it in every direction; in other words, it scatters, or *diffuses*, the light. The difference in the phenomena in the two cases is caused by the difference in the smoothness of the two

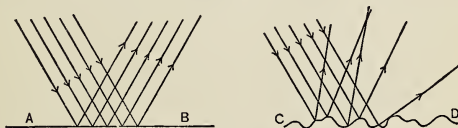


FIG. 142

reflecting surfaces. AB (Fig. 142) represents a smooth surface, like that of glass, which reflects nearly all the rays of light in the same direction, because nearly all the points of reflection are in the same plane. CD represents a surface of paper having the

roughness of its surface greatly exaggerated. The various normals at points of incidence are turned in every possible direction; consequently, light is reflected in every direction. Thus, the dull surfaces of various objects around us reflect light in all directions, and are consequently visible from every side.

194. Reflection from Plane Mirrors ; Virtual Images. — *MM'* (Fig. 143) represents a plane mirror, and *AB* a pencil of divergent rays proceeding from the point *A* of an object, *AH*. By erecting perpendiculars at the points of incidence, or the points where these rays strike the mirror, and making the angles of reflection equal to the angles of incidence, the paths *BC* and *EC* of the reflected rays are found.

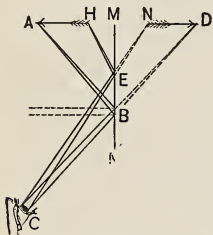


FIG. 143

Every visible point of an object sends a cone of rays to the eye.

The point always appears at the place whence these rays seem to emerge, *i.e.*, at the apex of the cone. If the direction of these rays be changed by reflection, or in any other manner, the point will appear to be in the direction of the rays as they enter the eye; thus, the point *A* appears to lie in the direction *CD* and the point *H* in the direction *CN*. The exact location of these points may be found by continuing each pencil of rays behind the mirror until it comes to a point, *CB* at *D*, *CE* at *N*. Thus, the pencils appear to emanate from these points, and the whole body of light waves received by the eye seems to come from an *apparent object*, *ND*, behind the mirror. This apparent object is called an

image. An image is a point or a series of points from which diverging pencils of rays come or appear to come. As of course no real image can be formed back of a mirror, such an image is called a *virtual* or an *imaginary* image. It will be seen, by construction, that an image in a plane mirror appears as far behind the mirror as the object is in front of it, and is of the same size and shape as the object.

EXERCISES

1. If a mirror were perfect, could it be seen?
2. Explain why it is difficult to read the image of a printed page in a plane mirror.
3. (a) Lay a mirror on a table and hold a sharpened pencil vertically over it. Is the image of the pencil erect or inverted? (b) Incline the mirror at an angle of 45° and keep the pencil vertical. What is the position of the image?
4. Stand your book on end on a table and open it so that the leaves make an angle of about 60° . Now place two mirrors in a similar position and place a pencil vertically midway between them and count the images of the pencil. How can more than one image be formed in each mirror?
5. An object lying in front of a plane mirror is moved 3 cm. farther away from the mirror. How much does this change the distance between the object and its image?

195. Reflection from Concave Mirrors. — Let MM' (Fig. 144) represent a section of a concave spherical mirror, which may be regarded as a small part of a hollow spherical shell having a polished interior surface. The distance in a straight line from M to M' is called the *diameter of the mirror*. C is the center of the sphere, and is called the *center of curvature*. G is the *vertex* of the mirror. A straight line, DG , drawn through the center of the curvature and the vertex is called the

principal axis of the mirror. A concave mirror may be considered as made up of an infinite number of small

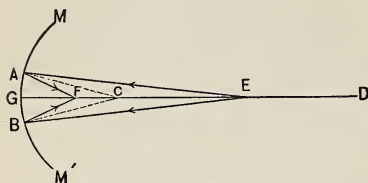


FIG. 144

plane surfaces. All radii of the mirror, as CA , CG , and CB , are perpendicular to the small planes which they strike. If C be a luminous point, it

is evident that all light waves emanating from this point and striking the mirror will be reflected to their source at C .

Let E be any luminous point in front of a concave mirror. To find the direction that rays emanating from this point take after reflection, draw any two lines from this point, as EA and EB , representing two of the infinite number of rays composing the divergent pencil that strike the mirror. Next, draw radii to the points of incidence, A and B , and draw the lines AF and BF , making the angles of reflection equal to the angles of incidence. Place arrowheads on the lines representing rays to indicate the direction of the motion. The lines AF and BF represent the direction of the rays after reflection.

It will be seen that the rays after reflection are convergent, and meet at a point, F , called a *focus*. This point is the focus of reflected rays that emanate from the point E . It is obvious that if F were the luminous point, the lines AE and BE would represent the reflected rays, and E would be the focus of these rays. Since the

relation between the two points is such that light waves emanating from either one are brought by reflection to the other, these points are called *conjugate foci*. *Conjugate foci are two points so related that the image of either is formed at the other*. The rays EA and EB , emanating from E , are less divergent than rays FA and FB , emanating from a point, F , less distant from the mirror. Rays emanating from D and striking the same points, A and B , will be still less divergent; and if the point D were removed to a distance of many miles, the rays incident at these points would be very nearly parallel. Hence, rays may be regarded as practically parallel when their source is at a very great distance, *e.g.*, the sun's rays. If a sunbeam, consisting of a bundle of parallel rays, as EA , DG , and HB (Fig. 145), strike a

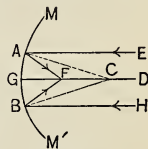


FIG. 145

concave mirror in a direction parallel to its principal axis, these rays become convergent by reflection and meet at a point, F , in the principal axis. This point, called the *principal focus*,¹ is about halfway between the center of curvature and the vertex of the mirror.

On the other hand, it is obvious that *divergent rays emanating from the principal focus of a concave mirror become by reflection parallel to the principal axis*.

The general effect of a concave mirror is to increase the convergence or to decrease the divergence of incident rays.

¹ The statement that parallel rays, after reflection from a concave mirror, meet at the principal focus, is only approximately true. The smaller the angle subtended at the center by the mirror, the more nearly true is the statement. It is strictly true only of parabolic mirrors, such as are used in the headlights of locomotives.

The following is a *formula for concave mirrors* :

$$\frac{1}{F} = \frac{1}{D_o} + \frac{1}{D_i},$$

in which F represents the distance of the principal focus from the mirror, and D_o and D_i represent, respectively, the distances of the object and the image from the mirror. Evidently, if any two of the three quantities involved be given, the third may be calculated.

196. Formation of Images. — To determine the position and kind of images formed of objects placed in front of a concave mirror, proceed as follows: Locate

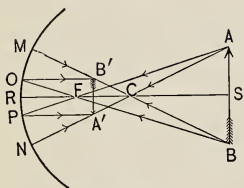


FIG. 146

the object, as AB (Fig. 146).

Draw lines, AN and BM , from the extremities of the object through the center of curvature C to meet the mirror. These lines are called *secondary axes*.

Incident rays along these lines will return by the same paths after reflection. Draw the

lines AP and BO through the principal focus F . The incident rays along the latter lines become by reflection parallel to the principal axis RS (§ 195). The images of points A and B are formed at the points A' and B' , respectively, where the reflected rays emanating from the corresponding points of the object meet after reflection. This image is called a *real image*, because the rays actually meet. The images of intermediate points between A and B lie between the points A' and B' ; consequently, the image of the object lies between the latter points as extremities.

It thus appears that an image of an object placed beyond the center of curvature of a concave mirror is real, inverted, smaller than the object, and located between the center of curvature and the principal focus of the mirror. A person standing in front of such a mirror, at a distance greater than its radius of curvature, will see an inverted image of himself suspended, as it were, in mid air.

Evidently, if $A'B'$ (Fig. 146) represent an object placed between the principal focus and the center of curvature, then AB will represent the image of the object.

Hence, the image of an object placed between the principal focus and the center of curvature is also real and inverted, but larger than the object, and located beyond the center of curvature. The image in this case may be projected upon a screen, but it will not be so bright as in the former case, because the light is spread over a larger surface.

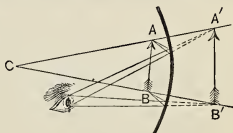


FIG. 147

Construct an image of an object placed between the principal focus and the mirror, as in Fig. 147. It will

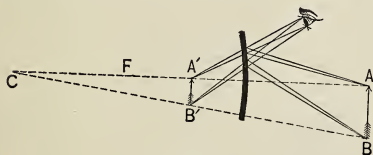


FIG. 148

be seen in this case that a pencil of rays proceeding from any point of an object, e.g. A , has no actual focus,

but appears to proceed from a *virtual* focus, A' , back of the mirror, and so with other points, as B . The image of an object placed between the principal focus and the mirror is virtual, erect, larger than the object, and back of the mirror.

Construct an image of an object, AB (Fig. 148), placed in front of a convex mirror. The pencil from A is reflected as if radiating from A' in the same axis AC , and that from B as from B' in the axis BC . The image $A'B'$ is found to be virtual, erect, and smaller than the object.

EXERCISES

1. An object is 10 feet from a concave mirror; a distinct image of the object is formed 2 feet from the mirror. (a) What is the focal length of the mirror? (b) Describe the image.

2. (a) The focal length of a concave mirror is 16 inches. At what distance from the mirror will the image of an object which is 18 inches from the mirror appear? (b) Describe the image.

SECTION IV

REFRACTION

197. Some Effects of Refraction. — In Fig. 149 is shown a rectangular tank having two glass sides, A and

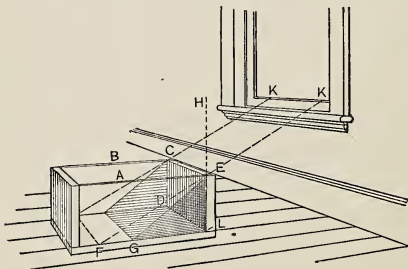


FIG. 149

B . Direct sunlight through a window casts a shadow of the end CL of the tank. EF is an edge of the

shadow. Now if the tank be filled with water (slightly clouded with milk, so as to render the illuminated portion clearly distinguishable from the shaded portion), the edge of the shadow will retreat to EG . That is, the rays of light that graze the upper edge EC are abruptly bent downward on entering the water, and move in paths *more nearly vertical*.

Experiment 1. — Place a coin at the bottom of a teacup. Look obliquely into the cup in such a manner that the coin is just hidden by the edge of the cup. Now, without moving the eye, fill the cup with water. The coin becomes visible and is seen at A' . A ray of light, AB (Fig. 150), on leaving the water at B , is bent in the direction BE . Observe that it is turned farther from a vertical line, CD ; also, that the coin and the bottom of the cup seem to be elevated or the water less deep than before.

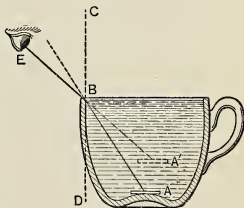


FIG. 150

Compare this with a fact that every boy has learned on wading into water, that he has to roll his trousers higher than previously seemed necessary, because the water is always deeper than it appears to be. If a lead pencil be thrust obliquely into water, it will appear bent at the surface of the water, and the immersed portion will appear shortened and raised nearer to the surface.



FIG. 151

If a narrow strip of thick plate glass with a straight piece of wire just back of it (Fig. 151) be held before the eye so that rays of light from the wire will pass obliquely through the glass to the eye, the wire will appear broken at the two edges of the glass, and the intervening section will appear moved either to the right or to the left, according to the inclination of the glass. But if the glass be not inclined, the wire does not appear to be moved to either side.

As long as a ray of light travels in the same uniform medium, its path is a straight line; but when it passes obliquely from one medium into another of different optical density it is bent, or *refracted*, at the interface between the two mediums. If it pass into a denser medium, it is refracted toward the perpendicular to this surface; if into a rarer medium, it is refracted from the perpendicular. A substance which has a higher refractive power than another is said to be *optically denser*.

The angle HEK (Fig. 149) is called the *angle of incidence*; LEG , the *angle of refraction*; and GEF , the *angle of deviation*.

198. Refraction due to Change of Speed. — The French physicist Foucault proved (1850) that light travels faster

in air than in water or glass. Indeed, it has been shown that light travels faster in a vacuum than in matter. It would seem that for some reason the ether is less elastic in matter than in a vacuum.

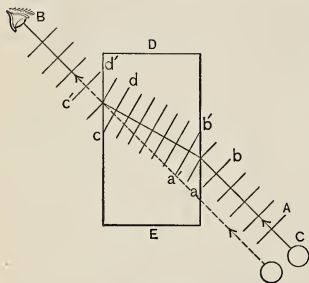


FIG. 152

Let the series of parallel lines AB (Fig. 152) represent a series of wave fronts

leaving an object, C , and passing through a rectangular piece of glass, DE , and constituting a beam. Every point in a wave front moves with equal velocity as long as it traverses the same medium; but the point a of a given wave front ab enters the glass first, and its velocity is impeded, while the point b retains

its original velocity; so that while the point a moves to a' , b moves to b' , and the result is that the wave front assumes a new direction (very much in the same manner as a line of soldiers executes a wheel) and a ray or a line drawn perpendicularly through the series of waves is turned out of its original direction on entering the glass. Again, the extremity c of a given wave front, cd , emerges from the glass first, when its velocity is immediately quickened, so that while d advances to d' , c advances to c' , and the direction of the ray is again changed.

It is evident that if the ray enter the new medium in a direction perpendicular to its surface, *i.e.*, with its wave front parallel to this surface, all parts of the wave front will be retarded simultaneously and no refraction will take place.

Since light waves travel with different velocities in different mediums, it follows that there must be a corresponding difference in the lengths of the waves in the different mediums. The ratio of the wave lengths in two mediums is equal to the ratio of the respective velocities in the two mediums.

199. Index of Refraction. — The deviation of light waves in passing from one medium into another depends upon the optical densities of the mediums and the angle of incidence. It diminishes as the angle of incidence diminishes, and is zero when the incident ray is normal to the surface. It is very important, when the angle of incidence is known, to be able to determine the direction which a ray will take on entering a new medium. Describe a circle around the point of incidence A (Fig. 153) as a center; through the same point draw IH perpendicular to the surfaces of the two mediums, and to this line drop perpendiculars BD and CE from the points

where the circle cuts the ray in the two mediums. Then suppose that the perpendicular BD is $\frac{8}{10}$ of the

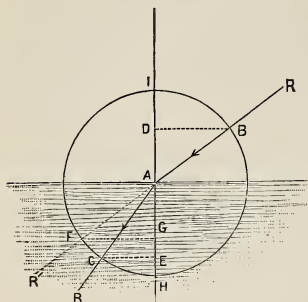


FIG. 153

radius AB ; now this fraction $\frac{8}{10}$ is called the *sine* of the angle DAB . Hence, $\frac{8}{10}$ is the *sine of the angle of incidence*. Again, if we suppose that the perpendicular CE is $\frac{6}{10}$ of the radius, then the fraction $\frac{6}{10}$ is the *sine of the angle of refraction*. The sines of the two angles are to

each other as $\frac{8}{10} : \frac{6}{10}$, or as 4 : 3. The quotient (in this case $\frac{4}{3} = 1.33 +$) obtained by dividing the sine of the angle of incidence by the sine of the angle of refraction (generally expressed decimally) is called the *index of refraction*. The incident ray may be more or less oblique, yet the quotient (*i.e.*, the index of refraction) remains the same.

200. Indices of Refraction. — When a ray passes from a vacuum into a material medium the refractive index is greater than unity, and is called the *absolute index of refraction*. The *relative index of refraction*, from any medium, A , into another, B , is found by dividing the *absolute index of B* by the *absolute index of A* .

TABLE OF APPROXIMATE ABSOLUTE INDICES

Diamond	2.5	Alcohol	1.37
Carbon disulphide	1.64	Pure water	1.33
Flint glass	1.56 to 1.78	Air at 0° C. and 760 mm.	
Crown glass	1.51 to 1.54	pressure.	1.00029

The reciprocals of the above indices represent the ratios of the velocity of light in these mediums to that in a vacuum.

201. Critical Angle; Total Reflection. — In Fig. 154 let SS' represent the boundary surface between two mediums and AO and BO incident rays in the more refractive medium (*e.g.*, glass); then OD and OE may

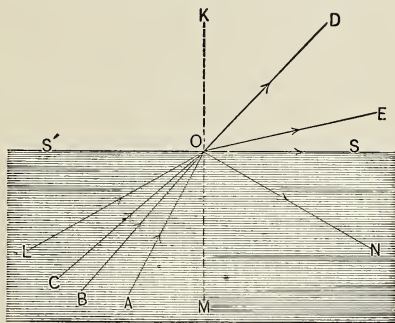


FIG. 154

represent the same rays, respectively, after they enter the less refractive medium (*e.g.*, air). It will be seen that as the angle of incidence is increased the refracted ray rapidly approaches the surface OS . Now there must be an angle of incidence (*e.g.*, COM) such that the angle of refraction will be 90° ; in this case the incident ray CO , after refraction, will just graze the surface OS . This angle (COM), which must not be exceeded if the ray is to pass out into the air, is called *the critical angle*. Any incident ray making a larger angle with the normal

than the critical angle, as LO , cannot emerge from the medium, and all such rays undergo internal reflection; *e.g.*, the ray LO is reflected in the direction ON . Reflection in this case is so nearly perfect that it has received the special name *total reflection*. *Total reflection occurs when rays in the more refractive medium are incident at an angle greater than the critical angle.* In other words, light cannot pass from a denser medium into air when the angle of incidence is greater than the critical angle.

Experiment 2. — Thrust the closed end of a glass test tube (Fig. 155) into water, incline the tube and look down upon the immersed part of the tube. Its upper surface resembles burnished silver.

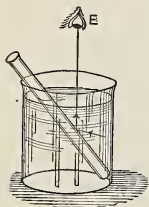


FIG. 155

Fill the test tube with water and immerse as before; the total reflection which before occurred at the interface between the glass and the air in the submerged tube now disappears.

The critical angle for water is $48^{\circ} 30'$; for flint glass $38^{\circ} 41'$; for diamond $23^{\circ} 41'$; and generally the higher the refractive index of any medium, the smaller is its critical angle.

Light cannot pass out of diamond at a greater angle than $23^{\circ} 41'$. Hence, it must be totally reflected internally, and the large quantity of light thus reflected is the cause of the brilliancy of this gem.

Glass is transparent, but when pulverized or broken into very small pieces it becomes opaque and snowy white, since

light cannot penetrate far into the mass without undergoing total reflection. In a similar manner, the whiteness of snow, its

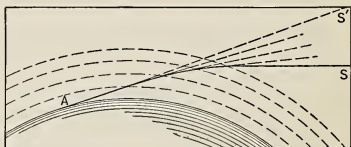


FIG. 156

opacity, and the dazzling intensity of the light reflected from it are accounted for.

A ray of light from a heavenly body, S (Fig. 156), undergoes a series of refractions as it reaches successive strata of the atmosphere of constantly increasing density, and to an eye at the earth's surface (*e.g.*, at A) appears to come from a point, S' , in the heavens. The general effect of the atmosphere on the path of light that traverses it is such as to increase the apparent altitude of the heavenly bodies. It enables us to see a body which is a little below the horizon, and prolongs the apparent stay of the sun, moon, and other heavenly bodies above the horizon. Twilight is due to both refraction and reflection of light by the atmosphere.

EXERCISES

1. Find the index of refraction of light in passing (*a*) from water into carbon disulphide, (*b*) from diamond into water.
2. Light travels with a velocity of 186,000 miles per second in a vacuum. What is the velocity of light in water?
3. (*a*) Does the amount of refraction depend on the obliquity with which light waves strike the surface of a medium? (*b*) Does the index of refraction depend on this?
4. When is one medium said to be optically denser than another?

SECTION V

PRISMS AND LENSES

202. Optical Prisms. — An optical prism is a portion of a transparent medium bounded by surfaces two of which are plane and inclined. Fig. 157 represents a transverse section of a common form of prism. Let AB be a ray of light incident upon one of its surfaces. On entering the prism it is refracted *toward* the normal, and takes the direction BC . On emerging from the

prism it is again refracted, but now *from* the normal in the direction CD . The object that emits the ray will

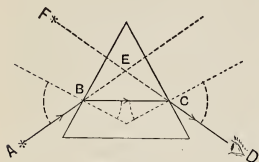


FIG. 157

appear in the direction DEF . Observe that the ray AB , at both refractions, is bent toward the thicker part, or base, of the prism.

203. Lenses. — Any transparent medium bounded by surfaces of which at least one is curved is a *lens*.

Lenses are of two classes, converging and diverging, according as they collect rays or cause them to diverge. Each class comprises three kinds (Fig. 158):

CLASS I	CLASS II
1. Biconvex 2. Plano-convex 3. Concavo-convex	4. Biconcave 5. Plano-concave 6. Convexo-concave.
} Converging or } convex lenses, } thicker in the } middle than at } the edges.	} Diverging or con- } cave lenses, thin- } ner in the middle } than at the edges.

A straight line normal to both surfaces of a lens and passing through their centers of curvature, as AB , is

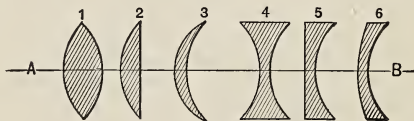


FIG. 158

called its *principal axis*. There is a point in the principal axis of every lens called its *optical center*. This point is so situated that a ray whose direction within the lens passes through it suffers no angular deviation,

but at most only a slight lateral displacement. In lenses 1 and 4 it is halfway between their respective curved surfaces.

204. Effect of Lenses. — Light waves emanating from a luminous point constitute a series of concentric hollow spheres. Near their source the wave fronts are much curved, but as the distance from the source increases and the spheres consequently become enlarged, the wave fronts become more and more nearly plane surfaces, and when the distance is very great the waves may be considered as having practically plane wave fronts. Such are the waves received from the sun. Fig. 159 represents a series of such waves, portions of which are transmitted through a biconvex lens, and the transfor-

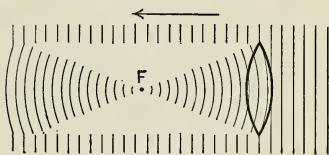


FIG. 159

mation from waves of plane front to waves of concave front due to refraction. It is plain that the energy of these transmitted waves must become concentrated at the point *F*, which is called the *focus* of these waves. A piece of cardboard held in the path of these waves will be intensely illuminated at this point for a brief time; but the waves being obstructed, their energy will soon be transformed into heat, and a small circular hole will be burned through the card.

It is, however, in many ways more convenient to study the relation of the *rays* than to follow up the wave front itself. Fig. 160 represents in diagram the same

phenomena, where only the *direction* of propagation of individual points in the wave front is considered. It will be seen by this diagram that incident rays parallel

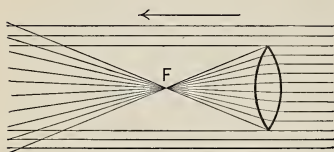


FIG. 160

to the principal axis of a convex lens are brought to a focus at a point, F , in the principal axis. This point is called the *principal focus* be-

cause it is the focus of incident rays parallel to the principal axis. It may be found by holding the lens so that the rays of the sun may fall upon it parallel to the axis, and then moving a sheet of paper back and forth behind it until the image of the sun formed on the paper is brightest and smallest. The focal length is the distance from the optical center of the lens to the center of the image on the paper. The shorter the focal length, the more powerful is the lens; that is, the

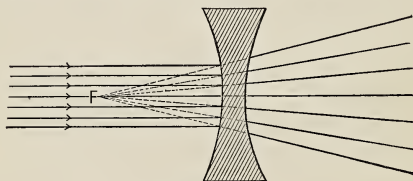


FIG. 161

more quickly are the parallel rays that traverse different parts of the lens brought to cross one another.

Rays emitted from the principal focus F (Fig. 160) as a luminous point become parallel on emerging from a

convex lens. If the rays emanate from a point nearer the lens, they diverge after egress, but the divergence is less than before; if from a point beyond the principal focus, they converge. A concave lens causes parallel incident rays to diverge as if they came from a point, as F (Fig. 161). This point is therefore its principal focus. It is, of course, a *virtual focus*.

It is apparent that the general effect of convex lenses is to cause transmitted rays to converge; that of concave lenses, to cause them to diverge.

205. Conjugate Foci. — When a luminous point, F_1 , beyond the principal focus (Fig. 162) sends rays to a convex lens, the emergent rays converge to another point, F_2 ; while rays sent from F_2 to the lens would converge to F_1 . Two points thus related are called *conjugate foci*.

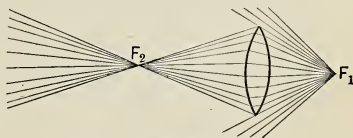


FIG. 162

to F_1 . Two points thus related are called *conjugate foci*.

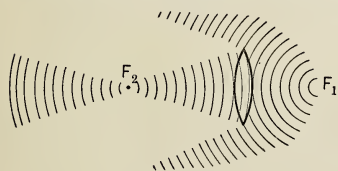


FIG. 163

Fig. 163 shows the corresponding changes in wave front. The fact that rays which emanate from one point are caused by convex lenses to collect at one point gives rise

to real images, as in the case of concave mirrors.

206. Law of Converging Lenses. — Lenses, like concave mirrors, have conjugate foci at distances D_o and D_i

from the optical centers. In converging lenses the principal focal distance and the distance of their conjugate foci (or distance of object and image) are related according to the same formula as given for concave mirrors, *viz.*,

$$\frac{1}{F} = \frac{1}{D_o} + \frac{1}{D_i}.$$

Hence the law of converging lenses: The reciprocal of the principal focal length is equal to the sum of the reciprocals of any two conjugate focal lengths.

If the object be at a greater distance than $2F$, the image is real and is on the other side of the lens at a distance greater than F and less than $2F$. If the object be at a distance greater than F but less than $2F$, the image is still real and at a distance greater than $2F$.

207. Construction of Images formed by Convex Lenses. — Given the lens L (Fig. 164), whose principal

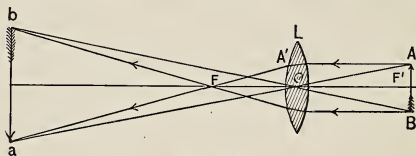


FIG. 164

focus is at F , and object AB in front of it, any two of the many rays from A will determine where its image, a , is formed. Two rays that can be traced easily are, one along the secondary axis,¹ AOa , and one, AA' , parallel to

¹ A secondary axis is a straight line drawn obliquely through a lens and passing through its optical center. Every ray that traverses this path is refracted just as though it had passed through a plane plate, and therefore leaves the lens in a direction parallel to the incident ray, suffering only a lateral displacement.

the principal axis; the latter will be bent so as to pass through the principal focus F' and will afterward intersect the secondary axis at some point, a ; therefore this is the conjugate focus of A . Rays can be similarly traced for B and all intermediate points along the arrow. Thus, a *real inverted image* is formed at ab .

It is evident that if ab represent the object, then AB will represent the image. In every case it will be found that

$$I : O = D_i : D_o,$$

in which I and O represent corresponding dimensions of the image and object, respectively, and D_i and D_o their respective distances from the optical center of the lens.

208. Virtual Images. — Since rays that emanate from a point nearer the lens than the principal focus diverge after egress, it is evident that their focus must be virtual and on the same side of the lens as the object. Hence, the image of an object placed nearer the lens than the principal focus is virtual, magnified, and erect, as shown in Fig. 165. A convex lens used in this manner is called a *simple microscope*.

209. Simple Microscope. — As its name implies, the microscope is an instrument for viewing minute objects. The simple microscope consists of a single converging lens so placed that the object is between the principal focus and the lens. It magnifies by increasing the visual angle.

The *magnifying power* of the lens is simply the ratio between the apparent linear dimension of the image and the corresponding dimension of the object, *e.g.*,

$A'B':AB$ (Fig. 165). If the lens be of short focus, as is usually the case, the magnifying power is approximately the ratio of the distance of distinct vision¹ to

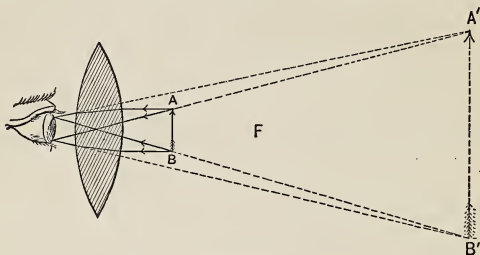


FIG. 165

the focal length. Thus, a lens of $\frac{1}{2}$ of an inch focal length would magnify twenty to twenty-four times.

210. Diverging Lenses. — Since the effect of concave lenses is to render transmitted rays divergent, pencils of rays emitted from A and B (Fig. 166) diverge after refraction, as if they came from A' and B' , and the image

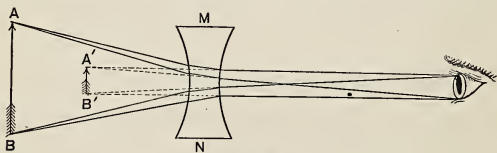


FIG. 166

appears to be at $A'B'$. Hence, images formed by concave lenses are virtual, erect, and smaller than the object.

¹ For normal eyes, an object to be seen most distinctly must be placed at a distance of 10 to 12 inches; hence, this is regarded as the distance of distinct vision.

EXERCISES

1. What must be the position of an object with reference to a converging lens that its image may be real and magnified?
2. A luminous point is 15 cm. from a convex lens having a focal length of 12 cm. Find the position of its image.
3. (a) Find the focal length of a lens which throws the image of an object 5 m. distant on a screen 2 m. distant. (b) Compare the size of the image with that of the object.
4. Will a convex lens converge the light as much when immersed in water as when it is in air?
5. Why can you not look very obliquely into water?
6. How would you locate an object, a screen, and a converging lens in order that the image should be four times the size of the object?
7. About what is the focal length of a simple microscope that magnifies thirty times?
8. About how many times does a lens of 2 inches focal length magnify?
9. (a) What is meant by the "power" of a simple microscope? (b) What is necessary that it may have great power?
10. To an eye whose distance of distinct vision is 25 cm. how many diameters will a lens of 1 cm. focal length magnify?

SECTION VI

PRISMATIC ANALYSIS OF LIGHT

211. Analysis of Sunlight. — For simplicity of treatment it has been thus far assumed that a ray of light when refracted is merely changed in direction. We are now to learn that a beam of white light, *e.g.*, a beam of sunlight, when it is refracted becomes separated into a large number of rays differing in refrangibility and color.

We will imagine ourselves to be in a room from which all light is excluded. Suppose that through a narrow

slit or crack in a window shutter a beam of direct sunlight is admitted. If a convex lens (not shown in Fig. 167) is placed in the path of this beam of light, a distinct image, AB (Fig. 167), may be projected upon the opposite wall of the room. We will next suppose a

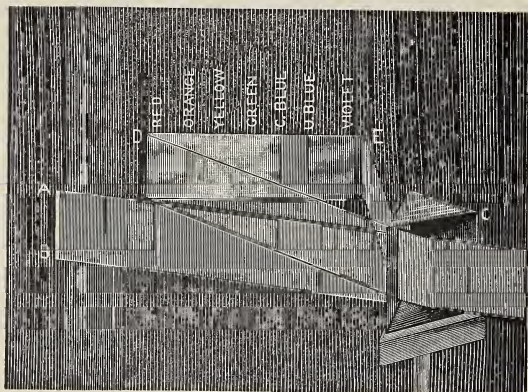


FIG. 167

glass prism, C , to be placed in the thin sheet of light after it emerges from the lens, as shown in the figure.

You now have revealed to you some remarkable phenomena which were first successfully investigated by Newton (1643–1727). (1) Not only is the light turned from its former path, but that which before was a narrow sheet is, after emerging from the prism, spread out fanlike into a wedge-shaped body, with its thickest part resting on the wall. (2) The image, before only a narrow vertical band, AB , is now drawn out into a long horizontal ribbon, DE . (3) The image, before white,

now presents all the colors of the rainbow, from red at one end to violet at the other; it passes gradually through all the intermediate gradations of orange, yellow, green, and blue.

We thus learn that (1) *white light is not simple in its composition, but the result of a mixture of colors*; (2) *the colors of which white light is composed may be separated by refraction*; (3) *the separation is due to the different degrees of deviation which colors undergo by refraction*. Red, which is least turned aside from a straight path, is the least refrangible color. Then follow orange, yellow, green, blue, and violet, in the order of their refrangibility. The many-colored ribbon of light *DE* is called the *solar spectrum*. This separation of white light into its constituents is called *dispersion*. The number of colors of which white light is composed is really indefinitely great, but we have names for only seven of them, *viz.*, *red, orange, yellow, green, cyan blue, ultramarine blue, and violet*; and these are called the *prismatic colors*.

212. Cause of Dispersion; Origin of Color. — While for convenience we find ourselves often using the word *ray*, we must not forget that there is no such thing as a ray: we must remember that in dealing with light we are dealing with *waves*. Light waves are not all of the same wave length. The difference of wave length makes itself known to our eyes as *color variations*. The light waves diminish in length from the red to the violet. As pitch depends on the frequency with which aërial waves strike the ear, so color depends upon the frequency with which ether waves strike the eye. The

difference between violet and red is a difference analogous to the difference between a high note and a low note on a piano.

In a vacuum the speed of propagation appears to be the same for all waves. But in a refracting medium the short waves are more retarded than the longer ones, hence more refracted. This is the cause of dispersion. Each wave length has its own refractive index, or, since vibration frequency corresponds to color, every simple color has its special refractive index. Light composed of waves all of the same (or nearly the same) length is called *homogeneous* or *monochromatic* light. The yellow light emitted by the flame of a Bunsen burner or alcohol lamp when powdered borax is sifted upon it is approximately monochromatic. Ordinary white light is a mixture of long and short ether waves.

From well-established data, physicists have calculated the wave lengths corresponding to each of the prismatic colors, and the results are approximately as follows :

COLORS OF THE SPECTRUM

NAME OF COLOR	WAVE LENGTH IN MILLIONTHS OF A CENTIMETER	WAVE LENGTH IN MILLIONTHS OF AN INCH
Extreme red	81	32
Red	65	26
Orange	58	23
Yellow	55	22
Green	51	21
C. blue	48	19
U. blue	45	18
Violet	40	16
Extreme violet	36	14

213. Rainbow.—The rainbow is an example of a solar spectrum on a magnificent scale caused by dispersion and reflection of light within falling raindrops.

If you will obtain from a glass blower a small spherical glass bulb filled with water and hold it in the sunlight, it will reflect back upon a white screen the rainbow colors. The sphere of water represents a sort of a magnified raindrop. Let us examine the results when white light from the sun falls upon a raindrop.

Suppose SA (Fig. 168) to be incident rays. They are twice refracted by the drop and totally reflected at its back surface. If an observer faces the drop with the sun shining on it from behind him so that the red components RR' when they emerge from the drop make an angle SXE of 42° , he will receive from this drop the impression of red. For violet

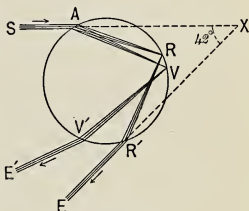


FIG. 168

light the angle is about 40° , and for other colors it has values intermediate between these. The eye at E is not in a position to receive the violet components $V'E'$, but must obtain them from drops in a circle lying within the circle of red. Hence, we see in the rainbow a set of concentric circles of all the colors of the spectrum from the red on the outside to the violet on the inside. The center of these circles is a point in space exactly opposite the sun in a line passing through the sun and the eye of the observer.

214. Chromatic Aberration.—There is in ordinary convex lenses a serious defect, called *chromatic aberration*, the correction of which has demanded the highest skill. The convex lens both *refracts* and *disperses* the light waves that pass through it. The tendency, of course, is to bring to a focus the more refrangible rays, as the violet, at a nearer point than the less refrangible

rays, such as the red. The result is a disagreeable coloration of the images that are formed by the lens, especially by those portions of the light waves that pass through the lens near its edges. This evil may be over-



FIG. 169

come very effectually by combining with the convex lens a plano-concave lens. Now if a crown-glass convex lens be taken, a flint-glass concave lens may be prepared that will correct the dispersion of the former without neutralizing all its refraction, since the refractive and the dispersive powers of the two kinds of glass are not proportional. A compound lens composed of these two lenses cemented together (Fig. 169) constitutes what is called an *achromatic lens*.

215. Spectroscope. — An instrument used for the examination of spectrums is called a *spectroscope*. It consists usually of a prism, or “dispersion piece,” and two astronomical telescopes. They are arranged as indicated in Fig. 170, where *F* is the source of light, *e.g.*,

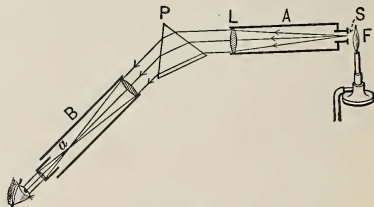


FIG. 170

a gas flame. The narrow slit *S* at the end of the telescope *A* admits a pencil of light, the rays of which are made parallel by means of the lens *L*. The parallel rays fall upon the prism *P*, but when they emerge from the prism every different color has a different direction.



SIR ISAAC NEWTON (1642-1727)

Profound mathematician, "Prince of Philosophers"; traced the principles which govern the motions of the planets in their orbits; formulated the Law of Gravitation; enunciated the Three Laws of Motion; discovered the principle of the different refrangibility of colors. Portrait after painting by Kneller, in Cambridge.

The spectrum, instead of being viewed upon a screen, is viewed through the telescope *B*. By placing a photographic plate at *a*, images of the slit may be photographed. In this manner valuable information in regard to the physical and chemical constitution of the sun and stars has been obtained.

216. Bright-Line Spectrum ; Spectrum Analysis. — If a platinum wire be dipped into powdered borax and placed in the almost colorless flame of a Bunsen burner (*F*, Fig. 170), the flame will be colored a deep yellow. Instead of a continuous spectrum of many colors, such as is described in § 211, you find only a bright line of yellow in the yellow region of the spectrum on a comparatively dark ground. (See Sodium, Plate I, frontispiece.)

Plate I also exhibits the spectrums obtained when salts of lithium, strontium, and potassium are successively introduced into the flame. Each of these salts contains a different metal; borax contains sodium; the other substances used contain, respectively, the metals lithium, strontium, and potassium. These metals, when introduced into the flame, are vaporized, and it is from their gases that we get the spectrums. *All incandescent gases give discontinuous or bright-line spectrums, and no two gases give the same spectrum.*

On these facts is based a method of chemical analysis whereby substances are detected by observing the bright lines of their spectrums, a branch of physical chemistry called *spectrum analysis*. This method of analysis far exceeds all others in point of delicacy. For example, the presence of a millionth part of a milligram of sodium carbonate can be detected in this manner.

217. Fraunhofer Lines. — The solar spectrum is found to contain a large number of fine dark lines transverse to its length. The colored picture of the solar spectrum

in Plate I shows a few of these lines. They were first mapped by Fraunhofer (1814), who distinguished several of the more prominent ones by letters of the alphabet; hence, the dark lines of the solar spectrum have received the name of *Fraunhofer lines*.

218. Explanation of Fraunhofer Lines and of Absorption Spectrums. — Suppose an electric lamp to be placed back of the Bunsen flame (Fig. 170) so that the white light of the electric lamp will pass through the flame colored yellow with some sodium salt. On examination by the spectroscope, there will be found a dark line in the yellow portion of the spectrum precisely where the bright sodium line (see § 216) will be if the electric light be extinguished. The vapor of sodium in the flame, while capable of emitting light waves of a particular length, is also capable of absorbing such waves coming from another source. This of course leaves the corresponding part of the spectrum darker than those parts where the energy of the waves has not been absorbed. If salts of lithium, potassium, strontium, etc., are used in a similar manner, there will be found in every case spectrums crossed by dark lines where you would expect to find bright lines. (See Spectrums of Lithium, etc., Plate I.)

Such spectrums are obtained only when light passes through mediums capable of absorbing waves of particular lengths; hence, they are commonly called *absorption spectrums*.

The dark lines in the solar spectrum may now be accounted for. For example, the dark line in the spectrum in the exact place where we should expect to find the bright sodium line shows

that between the hot body of the sun, called the *photosphere*, and ourselves there is a cooler solar atmosphere containing sodium vapor. It is due to the missing waves which are absorbed by this vapor that this dark line is found in the solar spectrum. The dark lines are dark, however, only by being viewed on a brighter background. Other dark lines in the solar spectrum demonstrate in the same way the existence of vapors of other substances in the sun's atmosphere.

Nearly all the lines of the solar spectrum have been found to be identical with those of spectrums given of known substances, from which it is concluded that these substances are present in the sun's atmosphere in the state of vapor, *e.g.*, sodium, iron, calcium, lithium, copper, nickel, aluminum, hydrogen, and many others.

219. Infra-Red and Ultra-Violet Waves. — The solar spectrum is not limited to the visible spectrum, but extends beyond it at each extremity. Spectroscopic analysis, besides sifting the waves of one color from those of another, is able to separate waves which do not produce the sensation of light from those which do. Those waves that lie beyond the red end of the visible spectrum are called the *infra-red* waves, while those that lie beyond the violet are called the *ultra-violet* waves. These invisible waves can produce visible pictures when they fall upon sensitized paper. The infra-red waves are longer and the ultra-violet shorter than the luminous waves.

The visible spectrum is limited by the physiological constitution of our eyes to vibration frequencies lying between 758,000,000,000 for the violet and 395,000,000,000 for the red ends. The actually existing spectrum, however, is many times longer than the visible part. In the ultra-violet portion of the spectrum energetic photo-chemical action takes place for ten times the distance of the visible part. In the infra-red portion of the spectrum

heat-giving waves extending over fifty times the space of the visible spectrum have been carefully studied by Professor Langley. The length of some of these waves is more than thirty times that of the longest light waves. These waves show striking peculiarities, especially with reference to their ability to pass through certain substances that are opaque to light waves.

220. Only One Kind of Radiation. — The fact that radiant energy produces three distinct effects — *viz.*, luminous, heating, and chemical — has given rise to a prevalent idea that there are three distinct kinds of radiation. There is, however, absolutely no proof that these different effects are produced by different kinds of radiation. Science recognizes in radiation no distinction but wave amplitude, wave length, and wave form. *The same radiation that produces vision can generate heat and chemical action.*

The fact that the infra-red and ultra-violet waves do not affect the human eye does not argue that they are of a different nature from those that do; it shows that there is a limit to the susceptibility of the human eye to receive impressions from radiation. Just as there are sound waves, some too long and others too short to affect the human ear, so there are ether waves, some too long and others too short to affect the human eye.

SECTION VII

COLOR

221. Color by Absorption. — By the color of an object is meant in part the *sensation* the eye gets when looking at the object. In physics it is found convenient to apply the term *color* to that which produces the sensation, which, as we have already learned, is a train of waves of

a particular length. When in future we shall speak of red waves, yellow waves, etc., it will be understood that we refer to waves of suitable length to produce the sensations of red, yellow, etc.

Color is not a property of any body. The red rose does not possess the property of redness. Held in different portions of the solar spectrum it appears red only when the red waves strike it; in other parts of the spectrum it appears quite different. This shows that the red rose is red not because it colors the light, but on account of some relation between the substance of the rose and the light which falls upon it. If a beam of sunlight be passed through a red glass, and the light that emerges from the glass be analyzed, the spectrum will show that the glass transmits copiously only red waves, that portion of the spectrum where the green and the blue waves ought to appear being dark and colorless. This shows that the glass absorbs nearly all the waves except the red waves. As the glass allows only the red waves to reach the eyes, it is apparent that the glass must look red. Color of objects so determined, usually known as *body color*, is said to be due to *selective absorption*.

In the case of an opaque object, for example the rose referred to above, the waves of white light penetrate a little way into the object and suffer selective absorption; those waves which escape absorption are reflected out and give color to the object. So the color ascribed to the rose is the very color it rejects.

White does not exist by itself; it is indeed the *fusion* of the entire spectrum. The simultaneous stimulation of the retina by all the visible colors in proper proportion results in a mental impression which we call *white*. No more does black exist. Black is theoretically the absence of light.

222. Theory of Color Vision. — The generally accepted theory of color vision is that suggested by Young and developed by Maxwell and Helmholtz. It supposes the existence of *three primary color sensations, red, green, and violet*. For each of these sensations there is provided on the retina of the eye a set of nerves especially adapted to produce it. When all these sets of nerves are excited simultaneously and with proper intensities, the sensation of white light is produced. Combined in proper proportions they produce the intermediate sensations. Thus, red and green sensations combined give yellow or orange; green and violet give blue, etc.

223. Color Blindness. — In this defect of vision one of the three color sensations, usually that of red, is assumed to be either wanting or deficient, so that the colors perceived are reduced to those furnished by the remaining two sensations, green and violet. This causes the red-blind person to confound reds, greens, and grays. In some rare cases the sensation of green or of violet is the one deficient.

224. Complementary Colors. — To produce the sensation of white it is not necessary that waves of all lengths should enter the eye. Two sets of waves properly chosen will suffice. Thus, yellow and ultramarine blue and any two opposite colors in the diagram (Plate I) combined will produce white. Any two colors which together produce white are said to be *complementary*. No two of the three primary colors spoken of above can be complementary, since the third sensation would be wanting.

225. Color Fatigue; After-Images.

Experiment 1. — On a piece of white paper lay a circular piece of blue paper, say 15 mm. in diameter. Attach one end of a piece of thread to the colored paper, and hold the other end in the hand. Place the eyes within about 15 cm. of the colored paper, and look steadily at the center of the paper for about fifteen seconds; then, without moving the eyes, suddenly pull the colored paper away. Instantly there will appear on the white paper an image of the colored paper, but the image will appear to be yellow.

This is usually called an *after-image*. If yellow paper be used, the color of the after-image will be blue; and, in general, whatever the color of an object, its after-image will appear in the complementary color. This phenomenon is explained as follows: When we look steadily at blue for a time the nerves that are excited by waves of this color become *fatigued* and less susceptible to their influence, while the other sets of nerves are fully susceptible to the influence of waves of other colors. Hence, when we are suddenly brought to look at white, which may be regarded as a compound of yellow and blue, we receive a vivid impression from the yellow constituent, and a feeble impression from the blue; hence, the predominant sensation is yellow.

226. Effect of Contrast. — When different colors are seen near each other at the same time their appearance differs more or less from that observed when they are seen separately. Thus, a red object, *e.g.* a red rose, appears more brilliant if a green object, *e.g.* green leaves, be seen in juxtaposition to it. Such effects are said to be due to *contrast*.

When any two colors given in the circle (Plate I) are brought into contrast, as when they are placed next each other, the effect is to move them farther apart in the color scale. For example, if red and orange be brought

into contrast, the orange assumes more of a yellowish hue, and the red more of a purplish hue. Colors that are already as far apart as possible, *e.g.*, yellow and blue, do not change their hue, but merely cause each other to appear more brilliant.

227. Mixing of Color Sensations.

Experiment 2.—On a black surface, *A* (Fig. 171), lay two small rectangular pieces of paper, one yellow and the other blue, about 2 inches apart. In a vertical position between these papers, and from 3 to 6 inches above them, hold a slip of plate glass, *C*. Looking obliquely down through the glass you may see the blue paper by transmitted light waves and the yellow paper by reflection. That is, you see the object itself in the former case, and the image of the object in the latter case. By a little manipulation the image and the object may be made to overlap each other, when both colors will apparently disappear, and in their place the color which is the result of the mixture will appear. In this case it will be white, or rather *gray*, which is *white of a low degree of luminosity*.

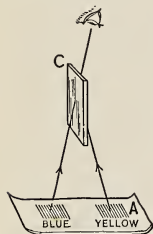


FIG. 171

The blending of several color sensations into one is beautifully shown by means of Newton's color disk (Fig. 173), which contains

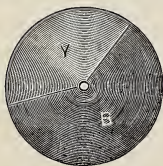


FIG. 172



FIG. 173

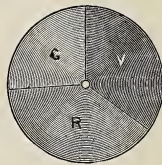


FIG. 174

sectors of the seven prismatic colors arranged in such proper proportion that when the disk is rapidly rotated the colors become

so blended in the eyes of the observer as to produce the sensation of gray. Yellow (Fig. 172) mixed with blue (less of the former being exposed, because it is a more intense color and tends to out-balance the blue) gives gray. The three primary colors, red, green, and violet (Fig. 174; see also right lower color diagram in Plate I) combined give gray.

228. Mixing Pigments. — Mixing color sensations and mixing colored pigments may produce very different results. As we have seen, the blending of yellow and blue sensations produces white. But if the two pigments chrome yellow and ultramarine blue be mixed, a green pigment is produced. When white light penetrates a little way into this mixture the yellow pigment absorbs the blue and all the colors of the spectrum below the green, and the blue pigment absorbs the yellow and all the colors above the green, leaving only green to be reflected out to the eye.

The color square 3 (Plate I) represents the result of the mixture of pigments 1 and 2, while 4 represents the result of the optical mixture of the same colors.

229. Color due to Interference. — Every lad has amused himself at times in blowing soap bubbles and has observed the beautiful play of colors on the bubbles as they move about in the sunshine. Every one has observed a display of iridescent colors on the surface of water when covered with a thin film of oil. These colors, which have a different origin from that of any so far discussed, furnish a most striking confirmation of the wave theory of light. We have learned how two trains of sound waves, when their opposite phases coincide, mutually destroy each other and produce silence.

Let us now see what must happen when light waves strike obliquely any thin transparent film like that of the soap bubble, or a film of oil on water. To simplify matters we will suppose that monochromatic light (*i.e.*, light of only one wave length), approximately that of a sodium flame, falls on the film. Let

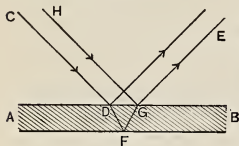


FIG. 175

AB (Fig. 175) represent a section of a transparent film greatly exaggerated in thickness. The incident waves along the path CD enter the film, are reflected from the rear surface at point F , and emerge from the film in the direction GE . Other waves, HG , are directly reflected at point G in the front surface of the film along the line GE . The two trains of waves join each other at G , but one has traveled farther than the other by a little more than twice the thickness of the film. Also the act of reflection from the second surface causes a reversal of phase which results in the loss of half a wave length. From this it will be seen that the two sets of waves will emerge in different phases, and according to the amount of this difference will the two trains of waves reënforce or destroy each other. An eye placed at E , in the former case, will see a bright yellow spot at G ; in the latter case it will see a dark spot. This shows that light added to light may produce darkness.

Next, let us suppose that the incident waves are white (*i.e.*, are waves of all lengths) and that the component yellow waves interfere as described. In the first case given above the bright yellow spot will be seen at G ; but in the second case the extinguishment of the yellow ingredient of the white light will leave its complementary blue. Hence, the eye will see at G a blue spot.

Newton observed these phenomena, but was unable to explain them satisfactorily by the corpuscular theory. The wave theory being admitted, it is apparent that a method is revealed by which wave lengths of light may be measured.

The quivering of the light and the rapid changes of color of the fixed stars, commonly called "twinkling," is due to

interference caused by the passage of light through an atmosphere of variable density, and not to anything going on at the stars themselves. "Light coming to the eye from a star so distant as to be practically a single luminous point arrives in waves which have traversed slightly unequal distances in an irregularly refracting and ever-changing atmosphere, and thus enter the eye in irregularly unequal phases. Now one color is extinguished, now another; the eye perceives colored light complementary to that momentarily lost."—DANIELL.

EXERCISES

1. (a) On what condition will an object appear black? (b) Is black properly speaking a color? (c) On what condition will an object appear white? (d) Is white a color? (e) On what conditions will an object appear blue?
2. (a) Upon what two things does the color of an object depend? (b) Upon what only does the color of light depend?
3. When only the red and green nerves of the retina are excited what color sensation do we have?

SECTION VIII

OPTICAL INSTRUMENTS

230. The Human Eye. — Fig. 176 represents a horizontal section of the most wonderful of all optical instruments, the eye. Covering the front of the eye, like a watch crystal, is a transparent coat, 1, called the *cornea*. A tough membrane, 2, of which the cornea is a continuation, forms the outer wall of the eye, and is called the *sclerotic coat*, or "white of the eye." This coat is lined on the interior with a delicate membrane, 3, called the *choroid coat*; the latter consists of a black pigment, which prevents internal reflection. The inmost coat, 4, called the *retina*, is formed by expansion

of the optic nerve *O*. The muscular tissue, *ii*, is called the *iris*; its color determines the so-called "color of the eye." In the center of the iris is a circular opening, *5*, called the *pupil*, whose function is to regulate, by invol-

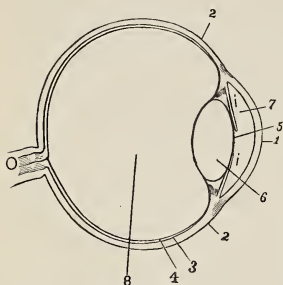


FIG. 176

untary enlargement and contraction, the quantity of light waves admitted to the posterior chamber of the eye. Just back of the iris is a tough, elastic, and transparent body, *6*, called the *crystalline lens*. This lens divides the eye into two chambers; the anterior chamber, *7*, is filled with a limpid liquid called the

aqueous humor; the posterior chamber, *8*, is filled with a jelly-like substance called the *vitreous humor*.

The eye may be likened to a photographer's camera, in which the retina takes the place of the sensitized plate. Images of outside objects are projected upon this screen by means of the crystalline lens assisted by the two humors, and the impressions thereby made on this delicate web of nerve filaments are conveyed by the optic nerve to the brain.

The convexity of the crystalline lens is susceptible to alteration within certain limits by muscular action so as to view near or distant objects. This alteration is called *accommodation*. An eye which can see an object most distinctly, without sense of effort, at a distance of 20 to 25 cm., is said to be a *normal eye*.

Nearsightedness occurs when the natural focal length of the eye is so short that the images of all but near objects are formed in front of the retina. This defect can be counteracted by concave lenses placed in front of the eyes to neutralize partially the refracting power of the crystalline lens, and thus to increase its focal length. *Farsightedness* occurs when the focal length of the eye is so great that images of near objects are formed back of the retina. In such cases convex lenses should be used to bring the focus forward to the retina.

231. Compound Microscope. — When it is desired to magnify an object more than can be done conveniently and with distinctness by a single lens, two convex lenses are used, — one, *O* (Fig. 177), called the *objective*, to form a magnified real image, $a'b'$, of the object ab ; and the other, *E*, called the *eyepiece*, to magnify this image so that the image $a'b'$ appears of the size $a''b''$. Instead of looking at the object as when we use a simple lens, we look at the real inverted image ($a'b'$) of the object.

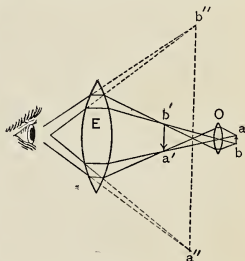


FIG. 177

232. Magnifying Power. — The magnifying power of a compound microscope is the product of the respective magnifying powers of the object glass and of the eyepiece; that is, if the first magnify twenty times and the other ten times, the total magnifying power is 200. The magnifying power is determined experimentally by means of a micrometer scale, for a description of which the student is referred to technical works on microscopy.

233. Telescope. — The telescope is used to view (scope) objects afar off (tele). The refracting telescope,¹ like the compound microscope, consists essentially of two lenses. The object glass O (Fig. 178) forms a real diminished image, ab , of the object AB ; this image,

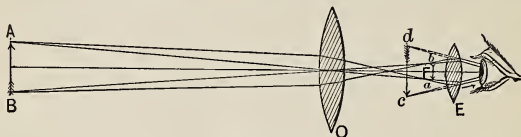


FIG. 178

seen through the eyeglass E , appears magnified and of the size cd . The object glass is of large diameter, in order to collect as much light as possible from a distant object for a better illumination of the image. If this lens has 100 times as much surface as the pupil in our eye, it will gather and bring to a focus 100 times as much light from a distant planet. The small lens E is simply a magnifier to help the eye to examine the image of a distant object formed by the object glass. The magnifying power of this instrument is approximately *the ratio of the focal length of the object glass to that of the eyeglass*. Increasing the *diameter* of the object glass, if the focal length be not changed, does not change the magnification; it will, however, change the *brightness* of the image.

¹ The earliest scientific discoveries with the aid of a telescope were made by Galileo with a refracting telescope constructed by himself (1610). Many persons who looked through it refused to believe their senses. Others refused to look through it. Among the latter was a professor of philosophy in the University of Padua, who declared that the telescope answered well enough for terrestrial objects, but was false and illusory when pointed at celestial bodies.

SECTION IX

THERMAL EFFECTS OF RADIATION

234. Heat not transmitted by Radiation. — We have learned that heat may travel *through* matter (by conduction) and *with* matter (by convection), and it is sometimes stated that there is a third method by which it travels, *viz.*, by “radiation.” Heat itself is not transferred by radiation at all; heat generates radiation (*i.e.*, ether waves) at one place, and radiation produces heat at another; it is *radiation* that travels, not heat. The energy does not exist as heat in the intervening space and, therefore, does not necessarily heat the substance filling that space. Heat can flow only one way, *viz.*, from a given point in matter to another point that is at a lower temperature; radiation travels in all directions. The sun sends us no heat, but it sends radiations which the earth transforms into heat; but it should be borne in mind that radiations are not heat, and *vice versa*.

235. Diathermancy and Athermancy. — The character of any given body determines largely what becomes of the radiations which strike it. If the nature of the body be such that its molecules can accept the motion of the ether, the ether vibrations are said to be *absorbed* by the body, and the body is thereby heated; *i.e.*, the undulations of ether are transformed into molecular energy, or *heat*. Glass, for instance, allows the sun’s radiations to pass very freely through it, and very little is transformed into heat; but if the glass be covered with the soot of a candle flame, the soot will absorb the

radiations and the glass will become heated. Observe how cold window glass may remain while radiations pour through it and heat objects in the room. *Only those radiations that a body absorbs heat it; those that pass through it do not affect its temperature.* Bodies that transmit radiations freely are said to be *diathermanous*, while those that absorb them largely are called *athermanous*.

Dry air is almost perfectly diathermanous. All of the sun's radiations that reach the earth pass through the atmosphere, which contains a vast amount of aqueous vapor. This vapor, like water, is comparatively opaque to long waves; hence, it modifies very much the character of the radiations which reach the earth.

The process by which our atmosphere becomes heated is as follows: The longer ether waves emitted by the sun are directly absorbed by the water vapor in the air. The shorter waves escape absorption and, falling on the earth, heat it. The warmed earth in turn loses its heat chiefly by radiation; but its radiations are quite different from those which it receives. The earth, being at a low temperature, can emit only long waves; but it is precisely these waves that are readily absorbed by the aqueous vapor of the atmosphere. Hence, the aqueous vapor in the atmosphere acts as a trap for the energy which comes to us from the sun.¹

Glass does not screen us from the sun's heat, but it can very effectually screen us from the heat radiated from a stove or any other terrestrial object. Glass is diathermanous to the sun's radiations (simply because they have already lost most of the very long waves by atmospheric absorption), but quite athermanous to other radiations. This is well illustrated in the case of hotbeds and greenhouses. The sun's rays pass through the glass of these inclosures almost unobstructed, and heat the earth; but

¹ Remove for a single summer's night the aqueous vapor from the air which overspreads the country [England], and you will assuredly destroy every plant capable of being destroyed by a freezing temperature. — TYNDALL.

the radiations given out in turn by the earth are such as cannot pass out through the glass, and hence the heat is retained within the inclosures.

236. All Bodies emit Radiations. — Hot bodies usually part with their heat much more rapidly by radiation than by all other processes combined; but cold bodies, like ice, emit radiations even when surrounded by warm bodies. This must be so, for since all molecules are in a state of motion and are surrounded by ether, they cannot move without imparting some of their motion to the ether. But in order that a body become colder by radiation it must lose more heat by this process than it receives.

237. Good Absorbers; Good Radiators. — Bodies differ widely in their absorbing and in their radiating power, and it is found to be universally true that *good absorbers are good radiators, and bad absorbers are bad radiators*. In both cases much depends upon the character of the surface as well as upon that of the substance. Bright, polished surfaces are poor absorbers and poor radiators, while tarnished, dark, and roughened surfaces absorb and radiate rapidly. Dark clothing absorbs and radiates more rapidly than light clothing.

CHAPTER VII

ELECTROSTATICS

SECTION I

PROPERTIES OF ELECTRIFIED BODIES

238. **Electrification.** — A person passing his hand along a cat's fur on a cold, dry winter's day may hear frequent crackling sounds coming from the fur and in a dark room may see faint sparks in its hair. A dry glass rod,

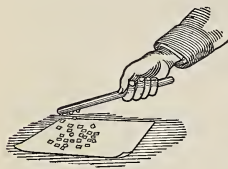


FIG. 179

immediately after being rubbed with dry silk, and a sealing-wax or ebonite rod, after being rubbed with woolen cloth, attract to themselves light articles like bits of paper (Fig. 179) or balls made of the pith of elder. Bodies of unlike substances, provided the conditions are suitable, acquire by contact and subsequent separation (or, conveniently, by rubbing one on the other) the power of attracting other bodies and one another. Bodies when in this state are said to be *electrified*. The attractive force which they manifest is called *electro-motive force*.

239. Two Kinds of Electrification.

Experiment 1. — Suspend a ball of elder pith, *C* (Fig. 180), by a silk thread. Electrify a glass rod, *D*, with a silk handkerchief

and present it to the ball; attraction at first occurs, followed by repulsion soon after contact. Next excite a stick of sealing wax or a rubber comb with a woolen cloth and present it to the ball which is repelled by the electrified glass; the ball is attracted by the electrified wax or rubber.

It is evident (1) that *there are two kinds of electrification*; (2) that *bodies similarly electrified repel one another*, and that *bodies oppositely electrified attract one another*.

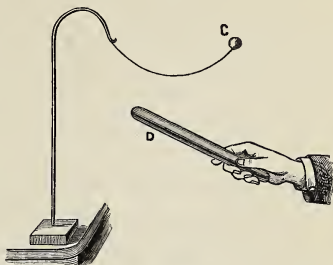


FIG. 180

Experiment 2. — Once more electrify a stick of sealing wax with a woolen cloth and present it to the pith ball, and after the ball is repelled bring the surface of the flannel which had electrified the rod near the ball; the ball is attracted by it, showing that the flannel is also electrified, and with the opposite kind of electrification to that which the sealing wax possesses.

One kind of electrification is never developed alone. When two bodies are rubbed together and one becomes electrified, electrification of the opposite kind is always developed on the other. Glass on being rubbed with silk is said to receive a *positive charge* ($+E$) and the silk a *negative charge* ($-E$). On the other hand, the wax on being rubbed with woolen cloth receives a negative charge and the woolen cloth a positive charge.

240. Electrification a Form of Potential Energy. — When two bodies are oppositely electrified it is found that they attract each other with a definite

and measurable force, and that this force varies inversely as the square of the distance between them.

The strained ether¹ between them is thought to operate like strained india-rubber bands, pulling the two bodies together. Work is required in order to separate the charged bodies, and the bodies thus separated possess *potential energy of electrical separation*.

241. The Electroscope. — This instrument is used to detect the presence of electrification in a body and also, if the body be electrified, to determine which of the two kinds of electrification it possesses. The electroscope consists of two strips of very light metal foil (*e.g.*, gold foil), *A* and *B* (Fig. 181), suspended from a metal rod. Frequently, for protection, the strips of foil are inclosed in a glass jar. The rod terminates at its upper extremity in a metal disk, *C*.

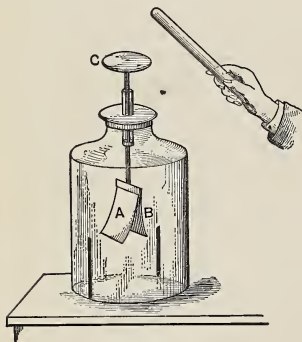


FIG. 181

(1) If an unelectrified body be brought near to or in contact with the disk, the strips of foil are not disturbed. If an electri-

fied body be brought near to or in contact with the disk, the strips of foil diverge as shown in the figure.

(2) To ascertain the *kind* of electrification present, it is necessary first to charge the disk with a known kind

¹ An electric charge is thought to be due to a strained condition of the ether surrounding the body.

of electrification. For example, we may charge the disk with $+E$ by bringing in contact with it a glass rod that has been excited, when some of the electrification of the glass rod will pass to the disk and flow down to the strips of foil. The two strips of foil thus receive light charges of $+E$, and both being charged with a like kind, they repel each other. Now if you bring a body charged with the same kind of electrification that the disk and foils have (in this case a body charged with $+E$) near to the disk, the strips of foil will diverge still more. But if the body have the opposite kind of electrification to that of the foils, the strips will collapse.

242. Conduction. — If, instead of a metal rod, a glass rod or a glass tube be used to connect the disk C of the electroscope with the strips of foil, it will be impossible to charge them by bringing a charged body in contact with the disk. The reason for this is that glass will not conduct electrification from the disk to the foils.

If you hold a brass rod in one hand and rub it with silk and then bring the rod near an electroscope, you will discover no indications of electrification. But if you place sheet rubber or several folds of silk between your hand and the brass rod, you will find by testing that the brass rod, after it has been rubbed with silk, is electrified. In the first case also electrification was generated on the brass rod when it was rubbed, but it was conducted away by your body to the earth as fast as it was generated, so that there was none left to affect the foils. In the last case the intervening rubber prevents the electrification from escaping. The brass rod

in this case is said to be *insulated* by the rubber, which is a non-conducting substance.

Some of the best insulating substances are *dry air, ebonite, shellac, resins, paraffine, glass, silks, and furs*. On the other hand, metals are exceedingly good conductors. Moisture injures the insulation of bodies; hence, experiments succeed best on dry days. Further, apparatus *should always be kept warm*.

A reservoir cannot retain water unless its walls be of sufficient strength; so a body, in order to retain a charge of electricity,¹ must be surrounded by something that will offer sufficient resistance to the escape of electricity. It may be air or any of the so-called non-conductors.

243. Dielectrics. — Fig. 182 represents an empty egg-shell covered with tin foil to make it a good conductor. It is suspended from a glass rod by a silk thread, which is a non-conductor. Thus, the surface is an insulated conductor. Electrify a glass rod and bring it near the shell. The shell will be attracted toward the rod. Next introduce a glass plate between the shell and the rod. The shell will move toward the rod as before.



FIG. 182

We learn from this experiment that, although air and glass prevent electricity from passing from the rod to the shell, they permit an influence (an attraction) through them. The same

¹ We use the term *electricity* here for the first time. In common parlance a little-understood *thing*, called *electricity*, is said to move along the conductor when a discharge takes place. Of electrification, its conditions and laws, we know much; of electricity we know nothing,— we have no knowledge of it apart from the electrified body; hence the propriety of commencing our study of the science by considering the phenomena of electrification.

would be found to be the case if any other non-conducting body were placed between the rod and the shell. Inasmuch as all non-conducting substances permit an electrical influence to be exerted through them, they are called *dielectrics*.

244. Induction. — Fig. 183 represents two shells so suspended that they touch each other, making practically one conductor. (1) Bring near to one end a sealing-wax rod charged with $-E$. While the rod is in this position, carry a strip of tissue paper, C , suspended from a glass rod along the shells. The paper will be attracted to the shells, *but most strongly to the ends*.

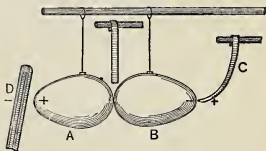


FIG. 183

(2) While the rod D is still in position, separate B from A ; then remove D . Test each shell with the tissue paper. Both will be found to be electrified.

(3) Test each shell with an electroscope. It will be found that shell A is charged with $+E$, and shell B with $-E$.

(4) Finally, bring the two shells near each other. They will attract each other. If the shells be allowed to touch, or be brought so near together that a faint spark passes between them, it will be found on testing them again that both have become *discharged*.

From these experiments we learn that when an electrified body is brought near to but not in contact with an insulated conductor, the electrified body acts through

the dielectric (in this case the air) upon the conductor, repelling electrification of the same kind to the remote side of the conductor, and attracting the opposite kind to the side near to it. Such electrical action is called *induction*.

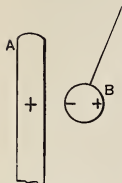


FIG. 184

When a pith ball, for instance, is brought near to an electrified glass rod, the $+E$ on the rod A (Fig. 184) induces $-E$ on the side of the ball B near to A , and repels $+E$ to the farther side.

The $+E$ of A and the $-E$ of B attract each other; likewise the $+E$ of A and the $+E$ of B repel each other; but since the like kinds are farther separated from each other than the unlike kinds, the attraction exceeds the repulsion.

SECTION II

ELECTRICAL POTENTIAL

245. Electrostatics and Electro-Kinetics. — Electricity may be at rest, as in a charged body, or it may be in motion, as when a charged body is discharged through a conductor to the earth. It will be shown later on that as long as a flow of electricity continues, the conductor along which it flows has properties different from those of a body upon which the charge is at rest. That branch of electrical science which treats of the properties of charges at rest is called *electrostatics*; and that branch which treats of electricity in motion is called *electrokinetics*.

246. Potential. — The fundamental fact of electricity is that *we are able to place bodies in different electrical*

conditions. A charge of electricity is a necessary antecedent condition to all electrical phenomena. We are now to discuss the meaning and use of the very important term *potential*, as it is employed in electrical science.

(a) When a charged conductor is connected with the earth, a transfer of electricity takes place between the body and the earth.

(b) If the body be charged with $+E$, we say arbitrarily that electricity passes from the body to the earth; but if the body be charged with $-E$, we say that electricity passes from the earth to the body.

(c) Whether electricity passes between two points of a conductor, and in which direction it passes, if at all, depends upon the relative *potentials* of the two points.

(d) If two bodies have the same potential, no transfer of electricity takes place between them; but if they have different potentials, there is a transfer, and the body *from* which the electricity flows is said to be at a *higher potential* than the body *to* which it flows.

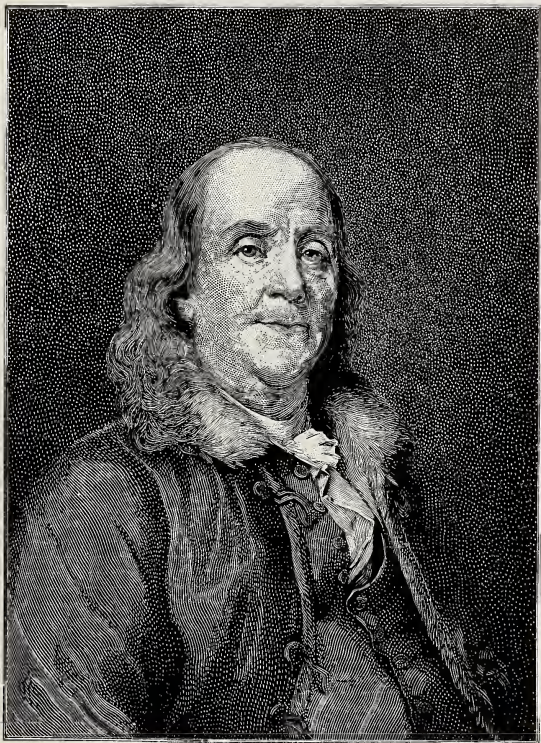
The potential of any point is the state of that point with reference to its tendency to communicate electricity to, or receive electricity from, other points. (See definition of temperature, § 100.)

The term *potential* is relative. It is important, therefore, to have a standard of reference whose potential is considered to be zero, just as it is convenient in stating the elevations or depressions of the earth's surface to give the distances above or below sea level, which is taken as the zero of height. For experimental purposes the earth is usually assumed to be at zero potential. A body charged with $+E$ is understood to be one that has

a higher potential than that of the earth, and a body charged with $-E$ one that has a lower potential than that of the earth. In like manner, when we say that the temperature of the air is 20° or -10° C., we mean that its temperature is 20° above or 10° below the standard temperature of reference, *viz.*, that of melting ice.

Potential is analogous, in many respects, to (1) temperature and to (2) liquid level. For (1) if two bodies at different temperatures be placed in thermal communication, heat will pass from the body at a higher to the one at a lower temperature and will continue to do so until both are at the same temperature; (2) and if two vessels containing water at different levels be connected by a pipe, water will flow from the higher to the lower level until the water is at the same level, when the flow ceases; so, also, (3) if two points having different potentials be electrically connected, that is, connected by a suitable conductor, electricity will always flow from the point at higher to the point at lower potential as long as a difference of potential between the two points is maintained.

247. Lightning.—Franklin, by his historic experiment with the kite in 1752, proved the exact similarity of lightning and thunder to the light and crackling of the electric spark. Certain clouds which have formed very rapidly are highly charged, usually with $+E$, but sometimes with $-E$. The surface of the earth and objects thereon immediately beneath the cloud are, of course, charged inductively with the opposite kind of electricity. The opposite charges on the earth and on



BENJAMIN FRANKLIN (1706-1790)

Renowned as an American statesman and as a scientist of original powers
Portrait after painting by Duplessis, in Boston Museum of Fine Arts.

the cloud hold each other prisoners by their mutual attraction, the air serving as an intervening dielectric.

As condensation progresses in the cloud, its potential rises (or sinks). This process continues till the difference of potential between the cloud and the earth becomes great enough to produce a discharge through the air. The noise of thunder and of sparks is due to the sudden expansion and collapse of the air along the path of discharge.

It is the accumulation of induced charges on elevated objects, such as buildings, trees, etc., that offers an intensified attraction for the opposite electricity of the cloud in consequence of their greater proximity, and renders such objects especially liable to be struck by lightning. The clouds gather electricity from the atmosphere. Our knowledge of the method by which the atmosphere becomes charged is very limited.

We see what we call a "flash of lightning." What we see is not electricity but air heated temporarily so as to be self-luminous. Lightning strokes last for a very brief time, — perhaps a millionth of a second, — though the sensation produced on the retina of the eye lasts longer.

EXERCISES

1. What causes one's hair to "fly" when brushed in cold weather?
2. Why, in the experiments described above, were sealing-wax and glass rods chosen in preference to metal rods?
3. (a) Is the energy of a *charge* of electricity potential or kinetic?
(b) Whence is the electric energy derived?
4. State some method of showing that there are two kinds of electrification.

5. On what condition will electricity pass from one body to another body, or from a point in a given body to another point in the same body?

6. (a) When glass is electrified by rubbing it with silk, does its potential become higher or lower than that of the earth? (b) Has sealing wax, after being rubbed with woolen cloth, a higher or a lower potential than that of the earth?

7. An electroscope is charged with $-E$. An insulated charged body is brought near it. (a) What do you infer as to the kind of charge the body has if the foils collapse? (b) if they diverge more?

CHAPTER VIII

ELECTRO-KINETICS — ENERGY DUE TO ELECTRIC FLOW

SECTION I

VOLTAIC CELLS — ELECTRIC CIRCUITS

248. Introduction. — Let *A* (Fig. 185) represent a tumbler partly filled with sulphuric acid much diluted with water. Into the acid are plunged a strip of zinc, *z*, and a strip of copper, *c*. Each of the metal strips has a copper wire soldered to its upper end. It may be shown experimentally,¹ by means of an electroscope, that the instant these strips are introduced into the acid both wires become electrified.

The wire joined to the copper strip becomes excited with $+E$, and the wire joined to the zinc with $-E$; or, as we learned in the preceding chapter, the potential of the former wire is raised, and that of the latter wire is lowered. It is evident, then, that if the two wires be brought into contact with each other, as shown in *B*, a discharge of electricity from the wire at higher potential to the wire at lower potential will instantly follow; but, as we shall learn later

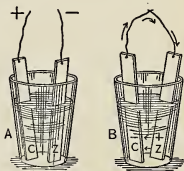


FIG. 185

¹ See the author's *Principles of Physics*, p. 463.

on, the discharge along the wire from the copper to the zinc is continuous, and such a discharge is known as an *electric current*.

249. Voltaic Cell. — An arrangement like the above, consisting of two solids, of which zinc is almost invariably one, placed in an electrolytic liquid (*i.e.*, a liquid capable of being decomposed by a current of electricity) constitutes a *voltaic cell*.¹ The two solids are called *elements*. It is necessary that one of the two elements should be more actively attacked by the liquid than the other; the one more acted upon (the zinc) is called the *electro-positive element*, and the other the *electro-negative element*.²

250. Electrical Circuit. — This term is applied to the entire path along which electricity flows; it comprises the electrolyte and the wire or other conductor connecting the elements. The operations of bringing the two extremities of the wire into contact and separating them are called, respectively, *closing and opening*, or *making and breaking, the circuit*. The free extremities

¹ The voltaic cell takes its name from Alexander Volta, who invented it in 1796.

² The following substances are arranged in order such that any one in the list is at the higher potential when put in contact with any one that follows it, but is at the lower potential when put in contact with any one before it in the list:

+	Zinc	Lead	Tin	Iron	Copper	Platinum	Carbon	-
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The difference of potential between zinc and carbon is equal to the sum of the differences of potentials between the intervening substances in the series. Consequently, other things being equal, these two substances of all given in this list are best for giving a strong current.

of the wires are called the *electrodes*, or *terminals*. The electrode of the negative element is called the *anode*, or the *positive electrode*, and that of the positive element is the *kathode*, or the *negative electrode*.¹

251. Origin of the Energy of Electric Flow. — In the voltaic cell difference of potential is produced by simple contact of the two elements with the electrolyte, or exciting liquid. When the wires joined to the two elements are brought into contact and a discharge takes place, electrical equilibrium would be produced and the current would cease were there not some means by which a difference of potential is maintained. This is accomplished by the chemical action all the time going on between the zinc and the liquid. The slow burning, or consumption, of the zinc serves to renew the difference of potential as fast as the discharges take place, and thus a continuous current is maintained while the circuit is closed.

The burning of zinc — in other words, the transformation of the potential energy of chemical separation which the zinc and acid possess into electrical energy — supplies the energy expended by the cell when the circuit is closed, somewhat as energy is

¹ The nomenclature in use, by which the zinc plate is called the *electro-positive element* and at the same time the *negative electrode* of the combination, is at first perplexing to the student. Let him bear in mind that electricity always flows from a point of high potential to a point of relatively low potential. For example, let a current originating in a voltaic cell at point *a* (Fig. 186) follow the direction indicated by the arrows; then point *c* must be negative with reference to point *a*, but positive with reference to point *d*; again, point *d*, while negative to point *c*, is positive to point *e*. The term *anode* signifies the *way up* (from the cell), and the term *kathode*, the *way down* (to the cell).



FIG. 186

supplied by a steam engine through the consumption of coal. *A voltaic cell is, therefore, a contrivance by which potential energy of chemical separation is converted directly into electrical energy.*

252. Local Action in Voltaic Cells. — When a voltaic circuit is open and there is no current the zinc ought not to be consumed, for this involves a useless consumption of zinc and a waste of energy. If the zinc be chemically pure, no chemical action takes place when the circuit is open. In practice, ordinary commercial zinc is used, and the zinc plate is irregularly eaten away, although on open circuit. This consumption of zinc is said to be due to *local action*. Local action is caused by the presence on the surface of the zinc plate of certain impurities, such as particles of carbon, iron, etc., which form numerous small local circuits. The zinc is thus eaten away around these particles. If mercury be rubbed over the surface of the zinc, it dissolves a portion of the zinc, forming with it a semi-fluid amalgam, which covers up the impurities and thus prevents local action, but does not impede the ordinary action of the cell on closed circuit.

253. Polarization of the Negative Element. — The current yielded by a cell like that described above rapidly weakens from the moment that the circuit is closed. This is shown by the diminution in the amount of work which the current can do. It will be noticed, also, that immediately on closing the circuit bubbles of gas are formed on the negative element. This accumulation of gas, which can be shown to be hydrogen, gives rise to what is called *polarization of the negative element*.

We know that difference of potential is indispensable to a flow of electricity. Difference of potential gives rise to something analogous to a force, which causes the flow of electricity. The greater the difference of potential, the greater is this agent which puts the electricity in motion; but a deposit of hydrogen on the copper raises, in some measure, the potential of this (negative) element and thereby diminishes the potential difference between the two elements. The gas also increases much the resistance to be overcome. Hence, the current is "weakened."

The usual remedy for this is to employ in addition to the exciting liquid some substance which will combine with the hydrogen as soon as it is liberated. A substance used for this purpose is termed a *depolarizer*. A mixture of a solution of crystals of potassium dichromate in water with a suitable quantity of sulphuric acid is used as a depolarizer in the so-called *dichromate cells*.

254. Daniell Cell. — The Daniell cell (Fig. 187) uses a solution which, instead of depositing hydrogen, deposits copper upon a copper negative plate, and hence is free from hydrogen polarization. It contains a copper negative and a zinc positive plate. The copper plate is immersed in a solution of copper sulphate, and the zinc in a solution of zinc sulphate or dilute sulphuric acid, a porous cup separating the two liquids. By the electrolytic action the zinc combines with the sulphuric acid (H_2SO_4), forming zinc sulphate (ZnSO_4), thereby setting hydrogen free. This hydrogen, while on its way to the negative element or the copper plate, meets the copper sulphate

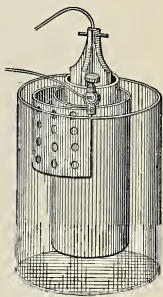


FIG. 187

solution (CuSO_4), which it decomposes, forming sulphuric acid again (H_2SO_4) and setting free the copper, which is deposited on the copper plate.

Since this cell does not polarize, it is especially adapted for *closed-circuit* work, that is, work requiring a steady current for a great length of time.

255. Bunsen Cell.—In this cell (Fig. 188) the negative plate is carbon and the depolarizer is usually a solution of potassium dichromate. Both this and the Daniell cell are called *two-fluid cells*. One of the two liquids used in these cells is inside, and the other outside, a porous earthen cup, which serves to prevent, in great measure, the two liquids from mixing.

256. Leclanché Cell.—There is a class of voltaic cells in which the negative element is protected somewhat from polarization by means of metallic oxides. Of these the best known is the

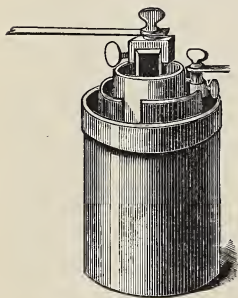


FIG. 188

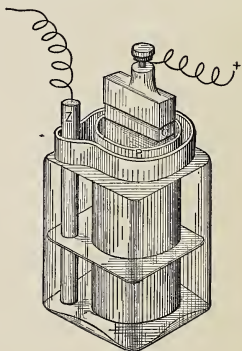


FIG. 189

Leclanché cell (Fig. 189). In this cell the carbon plate *C* is contained in a porous cup, *P*, and packed round with fragments of gas-retort coke and manganese peroxide. The manganese compound has a strong affinity for the hydrogen. Nevertheless, the

elements quickly polarize when in action. They need periodical rest to recover their normal condition. Such are called *open-circuit cells*, since they are suited for work only on lines kept open or disconnected most of the time, as in telephone and bell-ringing circuits. The zinc rod *Z* is immersed in a solution of ammonium chloride, which is the exciting liquid.

EXERCISES

1. (a) What are electrodes? (b) What are the essential parts of a voltaic cell? (c) What metal is almost invariably used for the positive element? (d) Name several substances commonly used for the negative element. (e) What happens when the electrodes are brought in contact? (f) What purpose does joining the two elements serve?

2. Why ought not the elements of a voltaic cell to touch each other?

3. What is the function of a voltaic cell?

4. If a current passes points *A*, *B*, *C*, and *D* in a circuit successively, (a) which point is positive with reference to all the others, and which point is negative with reference to all the others? (b) State the relation of point *B* to each of the other points.

5. With what propriety is the zinc element of a voltaic cell called the *positive element* and the *negative electrode* of a voltaic system?

6. (a) What do you understand by the "polarization of the negative element"? (b) How is it caused? (c) What harm does it do? (d) How is it commonly prevented?

7. Which, electricity or electrification, is the result of work done?

8. (a) What is meant by "local action"? (b) Why is it objectionable? (c) How is it prevented in some measure in certain cells?

9. What kind of cells are suitable for only "open-circuit" systems?

10. Which of the several cells that have been described will yield a current most nearly uniform or constant? Why?

SECTION II

EFFECTS PRODUCIBLE BY AN ELECTRIC CURRENT

257. Classification of Effects.—The several effects producible by an electric current may be classified as *electrolytic, magnetic, thermal, and physiological.*

258. Electrolysis.

Experiment 1.—Take a dilute solution of sulphuric acid (one part by volume to ten) and pour some of it into the funnel (Fig. 190) so as to fill the U-shaped glass tube when the stoppers are removed. Place the stoppers which support platinum electrodes tightly in the tubes. Connect with these electrodes the battery¹ wires. Instantly bubbles of gas arise from both electrodes, accumulating in the upper part of the tube and forcing the liquid back into the funnel. Introduce a glowing splinter into the gas surrounding the + electrode: it relights and burns vigorously, showing that the gas is oxygen. Invert the U-tube, remove the rubber tube, allow the gas which had accumulated about the - electrode to escape at A, and apply a lighted match to it: the gas burns; it is hydrogen.

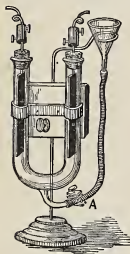


FIG. 190

The volume of hydrogen is just double that of the oxygen liberated in the same time. The process by which a compound substance is separated into its constituents by an electric current is called *electrolysis*, and a compound that may be thus decomposed is called an

¹ A battery consisting of not less than two Bunsen, or three Daniell, cells connected in series will be required. For the pupil's use a very inexpensive Daniell cell, such as is now in general use in high-school laboratories, is recommended.

electrolyte. The electrode by which the current enters the electrolyte is called the *anode*, and that by which the current leaves, the *kathode*. Those constituents that appear at the anodes are called *anions*; those that appear at the kathodes are called *kations*. Anions are electro-negative and kations are electro-positive; hence, they are attracted to electrodes that are oppositely electrified. Thus, *oxygen*, being electro-negative, is attracted to the anode, or positive electrode, and *hydrogen*, being electro-positive, is attracted to the kathode, or negative electrode. When a chemical salt is electrolyzed the base appears at the kathode, and the acid at the anode. In general, it will be found that in both the battery and the decomposing cell, hydrogen, bases, and metals appear at the plates *toward* which the current flows.

259. Magnetizing Effect of an Electric Current; Electro-Magnets.

Experiment 2. — (a) Wind an insulated copper wire in the form of a spiral round a rod of soft iron (Fig. 191). Pass a current of electricity through the spiral, and hold an iron nail near the end of the rod. Observe, from its attraction for the nail, that the rod is magnetized. A magnet may be provisionally defined as a body which attracts iron.

(b) Break the circuit; the nail drops, showing that the rod has lost its magnetism.

The iron rod is called a *core*, the coil of wire a *helix*, and both together an *electro-magnet*. In order to take advantage of the attraction of both ends, or *poles*, of the magnet, the rod is frequently bent into a U-shape (A,



FIG. 191

Fig. 192). Often two iron rods are used, connected by a rectangular piece of iron, as *a* in *B* of Fig. 192. This piece of iron, called a *yoke*, constitutes a part of the electro-magnet. The method of winding is such that

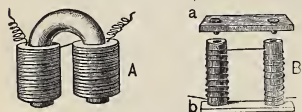


FIG. 192

if the iron core of the U-magnet were straightened, or the two spools were placed together end to end, one would be a continuation of the other.

For method of winding a U-magnet see also Fig. 221. A piece of soft iron, *b*, placed across the ends and attracted by them, is called an *armature*.

Fig. 193 represents a 50-pound weight supported by the magnetic effect of an electric current yielded by a battery of two Bunsen cells.

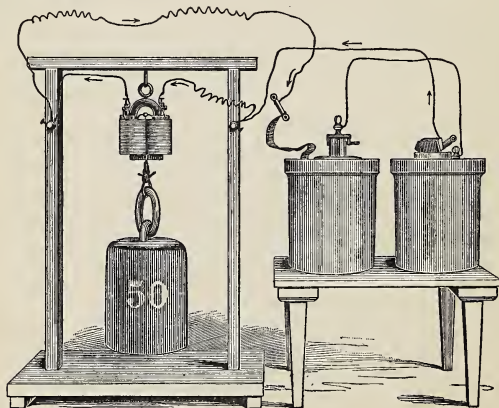


FIG. 193

260. Deflection of the Magnetic Needle by a Current.

Experiment 3. — (a) Place the apparatus (Fig. 194) so that the magnetic needle, which points north and south, shall be parallel to the wires W_1 and W_2 . Introduce the anode of a single cell into screw cup T_2 and the kathode into screw cup T_1 , and pass a current northward through the upper wire. At the instant the circuit is closed the needle swings on its axis and, after a few oscillations, comes to rest in a position which forms an angle with the wire bearing the current.

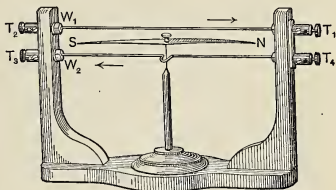


FIG. 194

(b) Break the circuit by removing one of the wires from the screw cup. The needle, under the influence of the magnetic action of the earth, returns to its original position.

(c) Reverse the current by inserting the anode of the battery into screw cup T_1 and the kathode into screw cup T_2 . Again there is a deflection of the needle, but the direction of the deflection is reversed; that is, the north-pointing pole (*N*-pole), which before turned to the west, is now deflected toward the east.

(d) Place your *right hand* above the wire, with the palm toward the wire and with the fingers pointing in the same direction as that in which the current is flowing, and extend your thumb at right angles to the direction of the current (Fig. 195). You observe that your thumb points in the *same* direction as the *N*-pole of the needle *under* the current-bearing wire.

(e) Reverse the current again (so that it shall flow northward), place your right hand as before (*viz.*, with the palm toward the wire and with the fingers pointing in the same direction as the current); your outstretched thumb still points in the *same* direction as the *N*-pole of the needle.

(f) Introduce the anode of the battery into screw cup T_3 and the kathode into screw cup T_4 , so that the current shall flow

northward *under* the needle. Place the right hand as directed before, except that it must be *under* the wire, so that the wire shall be between the hand and the needle; the thumb will point

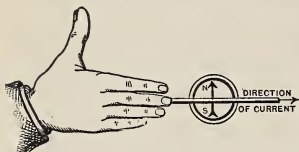


FIG. 195. — Right hand above the wire; needle below it



FIG. 196. — Right hand below the wire; needle above it

in the same direction as the *N*-pole (Fig. 196). Reverse the direction of the current in this wire and apply the same test; the same rule holds.

The rule for determining the direction of the deflection of the *N*-pole of a needle when the direction of the current is known is this: Place the outstretched right hand over or under the wire, so that the wire shall be between the hand and the needle, with the palm toward the needle, the fingers pointing in the direction of the current and the thumb extended laterally at right angles to the direction of the current; then the extended thumb will point in the direction of the deflection of the *N*-pole.

It will be observed that a deflection is reversed either by reversing the current or by changing the relative positions of the wire and needle, *e.g.*, by carrying the needle from above the wire to a position below it, or *vice versa*.

The force exerted by the current upon the needle in deflecting it is called an *electro-magnetic force*.¹

¹ The science of electro-magnetism originated with the discovery (1819) by Oersted of the deflection of a magnetic needle by an electric current.

261. Simple Galvanoscope, or Current Detector.

Experiment 4. — Introduce the + electrode of the battery into screw cup T_2 (Fig. 194) and the - electrode into screw cup T_3 , so that the current shall pass above the wire in one direction and below it in the opposite direction, as indicated by the arrows. *A larger deflection is obtained than when the current passes the needle only once.*

If the right-hand test be applied, it will be seen that the tendency of the current, both when passing the needle in one direction above and when passing it in the opposite direction below, is to produce a deflection in one and the same direction; consequently, the two parts of the current combine to produce a greater deflection.

If a more sensitive instrument be required, that is, one in which a weaker current will produce a sensible deflection, it will be necessary to pass the current through an insulated wire wound many times around the needle. Such an instrument is called a *galvanoscope*, or *current detector*, since one of its important uses is to detect the presence of a current.

262. Thermal and Luminous Effects of the Electric Current.

Experiment 5. — Construct a low-resistance battery (§ 279) of three or four cells, and introduce into the circuit a platinum wire, No. 30, about $\frac{1}{4}$ of an inch long. The wire very quickly becomes white hot, *i.e.*, it emits white light, which indicates a temperature of approximately 1800°C .

This experiment illustrates the conversion of the energy of an electric current into heat energy. In this case the energy of the current is consumed in

overcoming the *resistance* which the conductor or the circuit offers to its passage. Heat is developed by a current in every part of the circuit, because all substances offer some resistance to a current, — in other words, because there are no perfect conductors. The small platinum wire offers much greater resistance than an equal length of a larger copper wire, whence the greater quantity of heat generated in this part of the circuit. All of the energy in any electric circuit that is not consumed in doing other kinds of work is changed into heat.

263. Physiological Effects.

Experiment 6. — Place one of the copper electrodes of a single voltaic cell on each side of the tip of the tongue. A slight stinging (not painful) sensation is felt, followed by a peculiar acrid taste.

SECTION III

ELECTRICAL QUANTITIES AND UNITS OF MEASUREMENT

264. Strength of Current; the Ampere and the Coulomb. — The magnitude of the effects producible by an electric current depends upon the magnitude of the current. For this reason, almost any effect might be adopted as a basis for measuring currents. For example, the quantity of hydrogen gas or of any metal liberated at the kathode in a given time by electrolysis might be adopted, since it is strictly proportional to the magnitude of the current, or, as it is technically termed, the *strength of the current*; the equivalent expressions are the quantity of electricity conveyed in a unit of time,

or, more briefly, the “rate of flow.” The unit of current strength actually adopted is the strength of the current which, passed through a solution of nitrate of silver (prepared “in accordance with standard specifications”), deposits silver at the rate of 0.001118 g. per second. This unit is called the *ampere*.

Quantity of electricity is expressed in units called *coulombs*. A coulomb of electricity is the quantity of electricity conveyed past a given point in a circuit *in 1 second* when the strength of the current at that point is 1 ampere. An ampere current, therefore, is a current that delivers a coulomb of electricity per second.¹

265. Electro-Motive Force; the Volt. — Liquid will flow from vessel *A* to vessel *B* (Fig. 197) provided the pressure be greater at the extremity *M* of the connecting pipe *C* than at the extremity *N*. The difference in pressure at these two points is proportional to the “head” of water in *A*, or to the vertical height *DE* of the liquid surface in *A* above the liquid surface in *B*. We might say that the flow of liquid is due to a *liquid-motive force* arising from the difference of pressure at the points *M* and *N*.

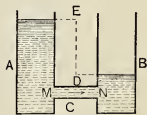


FIG. 197

¹ The definitions of the coulomb and the ampere here given are those of the so-called *international units*, which were adopted as the legal units by act of the United States Congress in July, 1894. Roughly expressed, the current strength employed in certain practical applications is as follows:

In electric welding, 20 to 50 kilo-amperes.

In arc lighting, 8 to 10 amperes.

In sixteen-candle-power incandescent lamps, 0.45 to 0.75 ampere.

In alternating current employed in the execution of criminals (New York state), 3 to 8 amperes, and an electro-motive force of about 1900 volts.

Similarly, electricity will flow in a conductor provided there be greater *electrical pressure* at one end of the conductor than at the other end. As long as such a difference of pressure is maintained, so long there will exist something that is analogous in many respects to a *current-producing force*. It is for this reason called *electro-motive force* (E.M.F.). *Electro-motive force is that which maintains or tends to maintain a current of electricity through a conductor.* Like a mechanical force, it has a definite direction. It does no work unless it moves electricity.

Difference in electrical pressure we have hitherto assumed to be due to difference of potential. Potential difference may be due to contact of dissimilar substances, as in the voltaic cell, or to the movement of a part of the conductor in a magnetic field, as in the dynamo. In every case it is due to an expenditure of energy of some kind.

The *volt* is the name chosen for the practical unit of E.M.F. and difference of potential. It is the electrical pressure required to maintain a current of 1 ampere against a resistance of 1 ohm (§ 266). Where great accuracy is not required it will answer to consider a volt as the E.M.F. of a Daniell cell.

266. Electrical Resistance; the Ohm. — Every substance offers resistance to the passage of a current. Those substances which offer a very powerful barrier are called *insulators*. The unit of resistance is called the *ohm*.

The international ohm is "the resistance offered to an unvarying electric current by a column of mercury

at the temperature of melting ice, 14.421 g. in mass, of a constant cross-sectional area, and of the length of 106.3 cm.”; or about the resistance of 9.3 feet of No. 30 (American gauge) copper wire (0.01 inch in diameter).

267. Electrical Power and Electrical Work or Energy. — When an electrical current of 1 ampere flows between two points in a conductor whose difference of potential is 1 volt, work is done at the expense of electrical energy (*i.e.*, electrical energy is transformed into heat or some other form of energy) at a rate called *a volt-ampere*, or *a watt*. Briefly, *the watt is the rate at which work is done in a circuit where the electro-motive force is 1 volt and the current is 1 ampere*.

If a coulomb of electricity flow between two points in a conductor whose difference of potential is 1 volt, a quantity of work is done, or a quantity of electrical energy is absorbed, that is called a *volt-coulomb*, or a *joule*.

The watt and the joule are, therefore, units of electrical power and electrical work (or energy), respectively. The volt-coulomb, or joule, is analogous to the kilogram-meter, and is equivalent to 0.1019+ kgm. $Watts = volts \times amperes$. $Joules = volts \times coulombs$. 746 watts are equivalent to 1 horse-power.

268. Résumé. — *An ampere current is a current maintained by an E.M.F. of 1 volt against a resistance of 1 ohm.*

An E.M.F. of 1 volt is the E.M.F. required to maintain a current of 1 ampere against a resistance of 1 ohm.

A conductor has a resistance of 1 ohm when an E.M.F. of 1 volt (or a difference of potential of 1 volt between its two ends) causes a current of 1 ampere to pass through it.

A power of 1 watt is the power of a current of 1 ampere maintained by a difference of potential of 1 volt.

A joule is the quantity of work done in 1 second by a current working at the rate of 1 watt.

269. Ohm's Law. — It is apparent that the rate of flow of water from vessel *A* to vessel *B* (Fig. 197) depends wholly upon the difference of level in the two vessels, the size of the pipe, and the resistance offered by the roughness of its interior surface. In like manner, the strength of an electric current between any two points in a conductor depends wholly upon the difference of potential of the two points (in other words, the E.M.F. which puts the electricity in motion), the size of the conductor, and the specific resistance of the substance of which it is composed.

The three factors, current strength (*C*), E.M.F. (or *E*),¹ and resistance (*R*), are interdependent. Their relations to one another are stated in the well-known Ohm's Law, thus: The current is equal to the E.M.F. divided by the resistance; or,

$$C = \frac{E}{R}; \text{ whence, } E = RC \text{ and } R = \frac{E}{C}.$$

Evidently, if any two of the three quantities are given, the third may be calculated.

The following are deductions from Ohm's Law:

C varies as E when R is constant.

C varies inversely as R when E is constant.

¹ In formulas it is necessary to represent E.M.F. by the single letter *E*.

E varies as R when C is constant.

Resistance in any circuit (R) is the ratio of the E.M.F. (E) to the current strength (C).

This famous law is the basis of a large proportion of the electrical measurements commonly made.

270. Galvanometer. -- This is an instrument for measuring current strength by means of the deflection of a magnetic needle. It is constructed on the principle that the stronger the current the greater will be the angle of deflection, though these are not often proportional.

A very simple form of this instrument is represented in sectional elevation and plan in Fig. 198. It consists of an insulated wire wound several times around a magnetic needle. The needle is poised on a point so as to be free to rotate. A card graduated like that of a mariner's compass is placed beneath the needle so that the number of degrees of deflection may be read from it.

The instrument is sometimes graduated to read the strength of the current in amperes, and when so constructed it is called an *ammeter* (a contraction of ampere-meter).

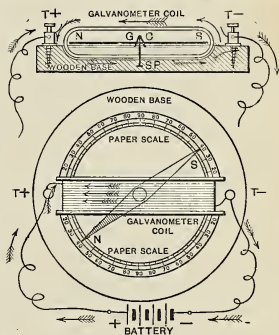


FIG. 198

EXERCISES

1. What do you understand by a *strong* electric current?
2. On what condition will a current flow between two points of a conductor?
3. If the rate of flow along a conductor be 5 amperes, how much electricity will pass along the conductor in 1 minute?

4. In what unit is difference of potential between two points in a conductor expressed?

5. (a) What is the difference of potential between the two elements of a Daniell cell? (b) What E.M.F. will a Daniell cell furnish?

6. (a) What is power? (b) What is the name of the unit of mechanical power? (c) of electrical power? (d) What is the equivalence between mechanical power and electrical power?

7. A current of 5 amperes is maintained by an E.M.F. of 8 volts. What is the power of this current?

8. The power of a certain current is 20 watts, and it is maintained by an E.M.F. of 10 volts. What is the strength of the current?

9. What E.M.F. is required to maintain a current of 10 amperes that it may yield a horse-power?

10. What is the resistance in a circuit when an E.M.F. of 1 volt maintains a current of 1 ampere?

11. What E.M.F. is required to maintain a current of 1 ampere through a resistance of 1 ohm?

12. An E.M.F. of 15 volts will maintain a current of 3 amperes through what resistance?

13. What current will an E.M.F. of 18 volts maintain through a resistance of 6 ohms?

14. A voltmeter (an instrument for measuring the difference of potential between two points) applied each side of an electric lamp shows a difference of potential of 40 volts. What current flows through the lamp if it offers a resistance of 10 ohms?

15. (a) If 120 coulombs of electricity be transferred through a circuit in 30 seconds, what is the average current strength? (b) What is the average power of the current if the E.M.F. is 2 volts?

16. If the fall of potential in an incandescent lamp be 110 volts and the strength of current maintained through it be $\frac{3}{4}$ of an ampere, what is the resistance of the lamp?

17. A current of 1 ampere and an E.M.F. of 70 volts are required to feed a certain incandescent lamp. What is the resistance of the lamp?

18. A Leclanché cell is used to ring a door bell. The resistance of the electro-magnet in the bell is 2 ohms, of the line wire $\frac{1}{2}$ of an ohm, and of the cell 1 ohm. The E.M.F. of the cell is 1.5 volts. What current is produced when the circuit is closed?

SECTION IV

RESISTANCE OF AN ELECTRIC CIRCUIT

271. External and Internal Resistance. — An electric circuit includes the generator (*e.g.*, voltaic battery, dynamo, etc.), the wire connectors, and whatever instruments are introduced into the circuit.

For convenience, the resistance of an electric circuit is divided into two parts, the *external* and the *internal*. External resistance includes all the resistance of a circuit except that of the generator, while that of the latter is termed internal resistance.

When the external resistance in a circuit is considered separately from the internal, Ohm's formula must be converted thus (calling the former R and the latter r):

$$C = \frac{E}{R + r}.$$

If the electrical dimensions of a cell be $E = 1$ volt and $r = 1$ ohm, and the connecting wire be short and stout, so that R may be disregarded, then the cell yields a current of 1 ampere. If by any means the internal resistance of this cell can be decreased one half, it will then be capable of yielding a 2-ampere current if the other conditions remain the same.

272. Resistance offered by Conductors. — C (Fig. 199) is a voltaic cell, G is a galvanometer, and S is a wooden platform on which are mounted spools of insulated¹ wire of different lengths, sizes, and kinds of metal.

¹ When wire is wound into close coils or on spools it is necessary that it be *insulated*, *i.e.*, covered with some non-conducting material in order to compel the electricity to flow throughout the entire length of the wire.

One of the spools of wire is represented as being connected in circuit with the cell and galvanometer by having the electrodes introduced into the screw cups each side of the spool. While the circuit is closed and the

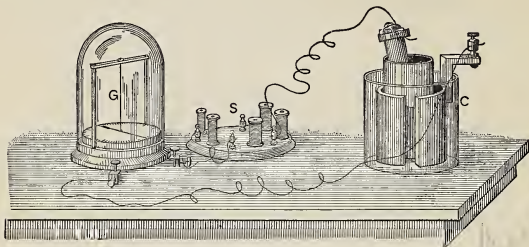


FIG. 199

current is circulating through the spool and galvanometer, the needle of the latter is deflected a certain number of degrees. Each of the several spools is introduced separately into the circuit, and the several deflections are noted. It is found that *the longer the wire is and the finer it is, the smaller is the deflection*. A smaller deflection indicates a weaker current. Since the E.M.F. of the cell does not change, it follows that weaker currents must be due to greater resistances. We therefore conclude that the resistance of wires increases with their length and fineness.

When means, such as will soon be explained, are adopted for measuring the resistance of conductors and comparisons are made, the following rules are deduced:

(1) Other things being equal, the resistance of a conductor is proportional to its length.

(2) Other things being equal, the resistances of conductors are inversely proportional to the areas of their cross sections. If the conductors be cylindrical (*e.g.*, wires), their resistances vary inversely as the squares of their diameters.

On introducing into the circuit, as explained above, spools of wire of different metals but of equal lengths and sizes, it is found that the deflections differ widely. From this we conclude that some metals offer less resistance than others; in other words, that some metals are better conductors than others. For example, copper offers about one sixth as much resistance as iron.

The particular resistance of a substance under specified conditions is called the *specific resistance* of that substance. (See Table of Resistance of Wire in the Appendix.)

Fig. 200 represents a piece of No. 7 (American gauge) wire 3.6 mm. (0.14 inch) in diameter. A mile of copper wire of this size offers a resistance of 2.62 ohms, or at the rate of 0.0005 ohm per foot. The resistance of a mile of iron wire of the same size is between 16 and 17 ohms.



FIG. 200

The resistance of metal conductors usually increases slowly with a rise of temperature of the conductor. The resistance of German silver is affected less by changes of temperature than that of most metals; hence its frequent use in standards of resistance. The resistance of carbon and all electrolytic conductors diminishes with a rise of temperature.

273. Resistance of a Voltaic Cell. — This is chiefly the resistance which the current encounters in traversing the electrolyte.

The resistance of a voltaic cell, other things being equal, varies inversely as the area of the cross section of the liquid between the elements.

In a large cell the area of the cross section of the liquid between the elements is larger than that in a small cell and, consequently, the internal resistance is less. This is the only way in which the size of the cell affects the current.

Obviously, the resistance of the battery would be increased by any increase of the distance between the elements, since this increases the length of the liquid conductor; but as this distance is usually made as small as convenient and is kept constant, it demands little of our attention.

EXERCISES

1. The resistance of 1000 feet of No. 24 copper wire (diameter = 0.511 mm.) is 26.284 ohms. What length of this wire would have a resistance of 0.5 ohm?
2. What is the resistance of 100 feet of No. 30 copper wire (diameter = 0.255 mm.)?
3. What is the resistance of 30 feet of No. 30 German-silver wire (the resistance of copper and German silver being as 1:12.8)?
4. State four things on which the resistance of a wire depends.
5. What is the resistance of $\frac{1}{2}$ of a mile of No. 30 copper wire 0.26 mm. in diameter?

SECTION V

DIVIDED CIRCUITS — MEASUREMENT OF RESISTANCE

274. Description of the Resistance Box. — Fig. 201 represents a cylindrical box containing a series of coils of German-silver wire whose resistances range from 0.1 ohm to 50 ohms, so that the total resistance is 160 ohms. The terminals of each coil are connected with brass blocks *A*, *B*, *C*, etc. (Fig. 202). When the brass plugs 1, 2, etc., are inserted between these blocks, the coils are short circuited, so that practically the whole current passes

through the plugs from block to block; but when a plug is withdrawn the current is obliged to traverse the corresponding coil. Thus, by withdrawing the proper plugs, any desired resistance within the capacity of the box may be thrown into the circuit. The resistance box is introduced into the circuit by connecting the battery terminals with the screw cups *A* and *B* (Fig. 201).

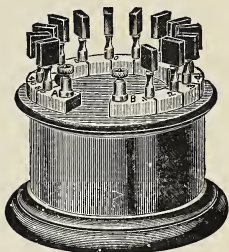


FIG. 201

275. Divided Circuits; Shunts.

— We will suppose a galvanometer, *G* (Fig. 203), to be introduced into a voltaic circuit and the deflection of the needle noted. Then let the por-

tion of the circuit between *a* and *b* be *divided* by connecting these points by another wire so that two paths are made by which the current may pass from *a* to *b*. Immediately the deflection in the galvanometer is

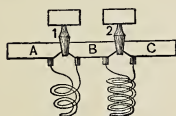


FIG. 202

diminished, which shows that there is less current now flowing through the galvanometer than there was before the circuit was divided. The current at point *a* divides, and a portion flows through each branch from *a* to *b*. Opening a new path between two points in a circuit is called *shunting* the circuit. The wire used in shunting is called a *shunt*.

Next we will suppose a resistance box, *R*, to be introduced into the shunt wire, and the resistance in the shunt branch to be gradually increased by increasing the resistance in the box. As the resistance

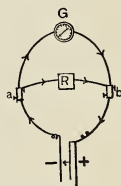


FIG. 203

of the shunt is increased, the current through the galvanometer is increased, as is shown by the increased deflections.

In a divided circuit the current is distributed between the paths in amounts inversely as their resistances. For example, if the resistance of the resistance box be 4 ohms, and that of the galvanometer be 1 ohm, then four fifths of the current will traverse the latter and one fifth the former.

Next we will suppose a galvanometer, G (Fig. 204), to be introduced into circuit with a spool of wire, A , and the deflection noted. Then let points a and b be shunted through another spool of wire, B . The deflection in the galvanometer is increased. Introducing the shunt virtually increases the size of the conductor between these two points, the effect of which is, of course, to diminish

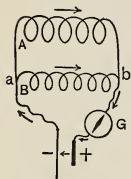


FIG. 204

the resistance between them. The resistance of the circuit being diminished, the current is increased.

Generally, the joint resistance of two branches of a circuit is the product of their respective resistances divided by the sum of the same quantities.

If any portion of a circuit be divided into three or more branches whose resistances are, respectively, r_1 , r_2 , r_3 , etc., it may be demonstrated that

$$\frac{1}{R} = \frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3} + \dots,$$

in which R represents the joint resistance of the several branches.

276. Measurement of Resistance by Means of a Wheatstone Slide-Wire Bridge. — Fig. 205 represents a simple form of Wheatstone bridge called a *slide-wire* bridge. On a wooden baseboard are fastened three bars of metal ad , ef , and gb . Each bar has at its ends screw cups for receiving wires. A German-silver wire, hi , is stretched between the end bars. G is a sensitive galvanometer connected as shown in the figure. C is a voltaic cell; R is a resistance box, by means of which a known resistance is introduced into the circuit between joints f and g ; and X is the resistance to be measured, *e.g.*, a spool of wire.

When the circuit is closed by inserting the electrode in screw cup b , a current passes throughout the whole arrangement, as shown by the arrows. It will be seen that between the two end bars

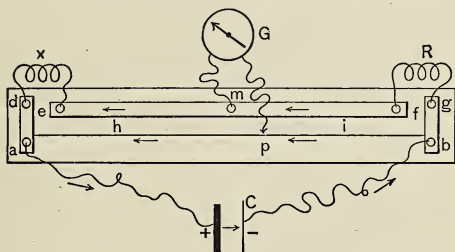


FIG. 205

there is a divided circuit, a part of the current flowing through each branch, *viz.*, fe and ih . Furthermore, these two branches are connected with each other at points m and p through the galvanometer G . This connection forms a sort of *bridge* between the two branches, whence the instrument derives its name. In general, points m and p will be at different potentials and a deflection will be produced in the galvanometer. By sliding this bridge wire along the wire ih , a point, p , may be found which has the same potential as point m ; then no current will traverse the bridge and there will be no deflection in the galvanometer. Point p now divides the German-silver wire into two parts, which

for convenience we will distinguish by the letters i and h . Points m and p can have the same potential, however, only on the condition that the ratio of the resistance R to the resistance X is equal to the ratio of the resistance of part i to the resistance of part h . But resistance of wires is proportional to their lengths. Hence, if we measure the lengths of parts i and h , the first three terms of the following proportion will be known, from which the resistance of X may be calculated:

$$\text{length } i : \text{length } h :: R : X.$$

SECTION VI

METHODS OF COMBINING VOLTAIC CELLS

277. E.M.F. of Different Cells. — If a galvanometer be introduced into a circuit with different kinds of cells, *e.g.*, Bunsen, Daniell, Leclanché, etc., very different deflections will be obtained, showing that the different cells yield currents of different strengths. This may be in some measure due to a difference in their internal resistances, but it is chiefly due to the difference in their electro-motive forces. We have learned that difference of E.M.F. is due to the difference of the chemical action on the two plates used and is wholly independent of the size of the plates; hence, the E.M.F. of a large cell is no greater than that of a small one of the same kind. Consequently, any difference in strength of current yielded by cells of the same kind but of different sizes is due wholly to a difference in their resistances.

The electro-motive forces of the Bunsen, Daniell, and Leclanché cells are, respectively, about 1.8, 1, and 1.5 volts.

278. Combining Cells ; Batteries. — A number of cells connected in such a manner that the currents generated by all have the same direction constitutes a *voltaic battery*. The object of combining cells is to get a stronger current than one cell will afford. We learn from Ohm's Law that there are two, and only two, ways of increasing the strength of a current. It must be done either by increasing the E.M.F. or by decreasing the resistance. So we combine cells into batteries, either to secure greater E.M.F. or to diminish the internal resistance. Unfortunately, both purposes cannot be accomplished by the same method.

279. Batteries of Low Resistance. — Fig. 206 represents three cells having all the + plates connected with one another, and all the - plates connected with one another, and the triplet + plates connected with the triplet - plates by the leading-out wires through a galvanometer, *G*.



FIG. 206

It is easy to see that since the circuit is divided by the battery into three parts, the internal resistance of the circuit, according to the principle stated in § 275, must be decreased threefold; in other words, the internal resistance of the three cells is one third of that of a single cell. This is called connecting cells in *multiple*, and the battery is called a *battery of low resistance*. The resistance of the battery is decreased as many times as there are cells connected in multiple, but the E.M.F. is equal to that of one cell only.

The formula for the current strength in this case is written thus :

$$C = \frac{E}{R + \frac{r}{n}},$$

in which n represents the number of cells. It is evident from this formula that when R is so great that $\frac{r}{n}$ is a small part of the whole resistance of the circuit, little is added to the value of C by increasing the number of cells in multiple.

280. Batteries of High Resistance or Great E.M.F. —

Fig. 207 represents four cells having the — plate of one connected with the + plate of the next, and the + plate at one end of the series connected by leading-out wires

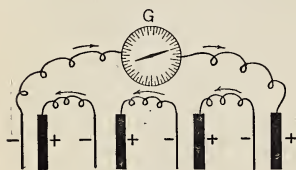


FIG. 207

through a galvanometer with the — plate at the other end of the series. This is called connecting cells *in series*. It is evident that the current in this series traverses the liquid four times, which

is equivalent to lengthening the liquid conductor four times, and of course increasing the internal resistance fourfold. But, while the internal resistance is increased, the *E.M.F. of the battery is increased as many times as there are cells in series*. In many cases (always when the internal resistance is a small part of the whole resistance of the circuit) the gain by increasing the E.M.F.

more than offsets the loss occasioned by increased resistance. This battery is called a *battery of high resistance* or *great E.M.F.*

The formula for current strength in this case becomes

$$C = \frac{nE}{R + nr}.$$

It is evident that C is increased most by adding cells in series when R is necessarily large compared with nr .

RULE FOR COMBINING CELLS: When the external resistance is large, connect cells in series; when the external is considerably less than the internal resistance, connect cells in multiple.

EXERCISES

1. What current will a Daniell cell whose resistance is 2 ohms maintain through an external resistance of 1 ohm?

2. What current will a Bunsen cell whose resistance is 0.8 ohm maintain through an external resistance of 0.5 ohm?

3. What current will a battery of 10 cells like that in Exercise 2 connected in multiple maintain through an external resistance of 0.5 ohm?

4. What current will a battery of 10 cells like that in Exercise 2 connected in series maintain through an external resistance of 0.5 ohm?

5. What current will 10 cells like that in Exercise 2 connected in multiple maintain through an external resistance of 8 ohms?

6. What current will 10 cells like that in Exercise 2 connected in series maintain through an external resistance of 8 ohms?

7. Compare the results obtained in the last four exercises and determine on what condition it is best to connect cells in multiple and on what condition it is best to connect them in series.

8. If a Bunsen cell maintains a current of 1.2 amperes through an external resistance of 0.5 ohm, what is the resistance of the cell?

9. (a) On what does the E.M.F. of voltaic cells depend? (b) On what does the resistance of voltaic cells depend?

10. When will a small cell give very nearly as strong a current as a large one?

11. (a) A Daniell cell, pint size, whose elements are connected by a short, stout copper wire which offers no appreciable resistance, will yield a current of about $\frac{1}{2}$ of an ampere. If the E.M.F. of the cell be 1 volt, what is the resistance of the cell? (b) If four such cells be connected in multiple by wires which offer no appreciable resistance, what current will the battery yield?

SECTION VII

MAGNETISM

281. **Magnets.** — Any body which attracts iron is called a *magnet*. A certain natural iron ore, called *magnetite* or *lodestone*, is found to possess this property. Given one magnet, it is possible to make any number of others. The simplest method is to take



FIG. 208

a small steel bar (*e.g.*, a darning needle) and draw one end of the magnet along it; the bar becomes a magnet. If a magnet be laid on a bed of iron filings and then removed, a mass of filings will be found clinging to its ends as shown in Fig. 208. The magnet appears to have a center of force at or near each end, while the central portion is devoid of magnetism.

282. **Magnetic Poles.** — If a magnetized needle (Fig. 209) be so supported at its center as to be free to rotate in a horizontal plane, it will take a position so as to point nearly north and south. That end of the needle which turns toward the north, when the needle is free

to rotate, is called the *north-seeking pole*, or simply the *north pole*. To render it at all times distinguishable from the opposite or south pole it is usually colored black. The north poles of other magnets are usually



FIG. 209

marked with the letter *N* or the plus sign (+), and the south pole with the letter *S* or the minus sign (−). A line joining the poles of a magnetic needle is called the *axis* of the needle. The direction assumed by the axis of a needle free to rotate is called a *magnetic meridian of the earth*.

283. Mutual Action between Poles; Magnetic Induction. — If a second magnet be brought near to a freely suspended magnet (Fig. 210), a mutual action between their poles will be noted as follows: *Like poles repel each other; unlike poles attract each other.*

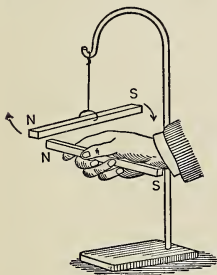


FIG. 210

When a magnet causes a piece of iron or steel, in contact with it or in its neighborhood, to become a magnet, it is said to magnetize the iron or steel by *induction*. As attraction, and never repulsion, occurs between a magnet and an unmagnetized piece of iron or steel, it must be that the magnetism induced in the latter is such that opposite poles are adjacent; that

is, an *N* or + pole induces an *S* or — pole next itself, as shown in Fig. 211.

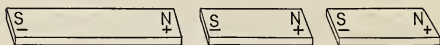


FIG. 211

It may be here remarked that if a magnet be broken into parts, the several parts will be found to be magnetized as shown in Fig. 211.

284. Retentivity and Resistance. — It is more difficult to magnetize steel than iron; on the other hand, it is difficult to demagnetize steel, while soft iron loses nearly all its magnetism as soon as it is removed from the influence of the inducing body. That property of steel in virtue of which it retains the magnetism which it has once acquired is called *retentivity*. The greater the retentivity of a magnetizable body, the greater is the *resistance* which it offers to becoming magnetized. *The harder steel is, the greater is its retentivity.* Hence, very hard steel is used for *permanent* magnets. Hardened iron possesses considerable retentivity; hence, the cores of electro-magnets should be made of the *softest* iron, that they may acquire and part with magnetism very quickly.

285. Forms of Artificial Magnets. — Artificial magnets, including permanent magnets and electro-magnets, are usually made in the shape either of a straight bar or of the letter U, according to the use to be made of them. If we wish to use but a single pole, it is desirable to have the other as far away as possible; then, obviously, the bar magnet is more convenient. But if the magnet is to be used for lifting or holding weights, the U-form (see Fig. 214) is far better, because the attraction of both poles is conveniently available.

SECTION VIII

LINES OF MAGNETIC FORCE — THE MAGNETIC CIRCUIT

286. Lines of Magnetic Force. — These lines are easily studied by the use of iron filings. The field of force around a magnet is shown by placing glass over it, dusting iron filings upon the glass, and tapping it. The filings take symmetrical positions, form curves between the poles of the magnet (Fig. 212), and show

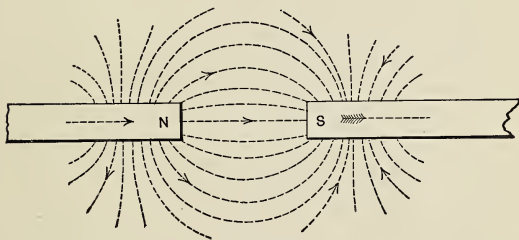


FIG. 212

that *the lines of force connect the opposite poles of the magnet*. The fact is that each filing, when brought within the magnetic field,¹ becomes a magnet by induction, and tends to take a definite position which represents the resultant of the forces acting upon it from each pole of the system. If a magnetic needle be placed in the field of a magnet, it will take a position such that its axis is tangent to the line of force passing through it.

¹ Surrounding every magnet there is a limited space through which magnetic influence extends, technically known as the *magnetic field*.

In Fig. 212 the unlike poles of two magnets are placed opposite each other. Fig. 213 is a diagram of lines of force of a bar

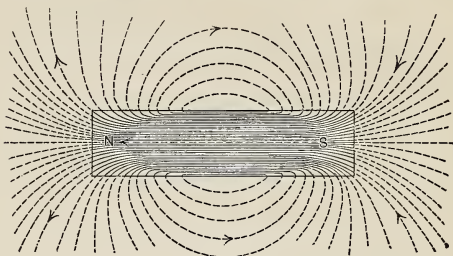


FIG. 213

magnet when its axis coincides with the magnetic meridian of the earth and its *N*-pole points north; and Fig. 214, of those of a

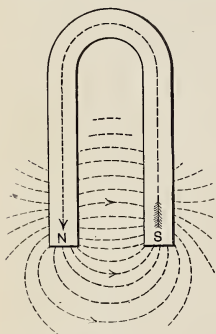


FIG. 214

U-shaped magnet. A *magnetic pole* is a region within a magnet toward which the lines of force converge or from which they diverge.

The direction of a line of force at any point is assumed to be the direction in which the *N*-pole of a magnetic needle would point if the needle were placed at that point. The *N*-pole of a magnet, as will be seen by examination of any of the figures here given, is the pole whence the lines of force

emerge, and the *S*-pole is the pole to which the lines of force converge. They do not stop at the *S*-pole, but continue through the magnet and form complete *closed circuits*.

287. Permeability to Lines of Force. — Lines of magnetic force are often regarded as *paths of magnetic flow*, much as the wires of voltaic circuits are regarded as paths of electric flow.

It would seem that air is a poor conductor of lines of force, or, to use a technical term, its *permeability* is low; on the other hand, iron is highly permeable to lines of force. If a piece of iron be brought within a magnetic field, many lines of force will leave their normal paths through the air and crowd together into and pass through this medium of greater permeability.

288. Magnetic Action of the Earth. — We have already seen evidence of this action in giving direction to the magnetic needle. The magnetic needle, in assuming its northerly and southerly position, indicates, as we have already learned, the direction of the magnetic meridian of the earth at the given place.

A magnetic needle supported on a horizontal axle so that it can rotate in a vertical plane is called a *dipping needle*. If such a needle be placed over the *N*-pole of a magnet, as shown in Fig. 215, it will take a vertical position with its

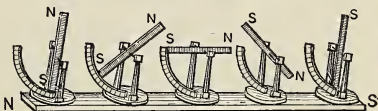


FIG. 215

S-pole down. Move the needle along the magnet; the needle will gradually rise until it reaches the middle of the magnet, where it becomes horizontal. Continue moving the needle toward the *S*-pole of the magnet; the *N*-pole of the needle now dips, and the dip increases until it reaches the *S*-pole of the magnet, where it again becomes vertical, with its *N*-pole down.

If the same needle be carried northward or southward along the earth's surface, it will dip in the same way as it approaches the polar regions, and be horizontal only at, or near, the equator.

Places where the dipping needle assumes a vertical position are called the *magnetic poles of the earth*.

Inasmuch as the magnetic poles of the earth do not coincide with the geographical poles, it follows that in most places the needle does not point due north and south. The angle which a vertical plane through the axis of a freely suspended needle makes with the geographical meridian of the place is known as the *angle of declination*. In other words, the angle of declination is the angle formed by the magnetic and the geographical meridians. This angle differs at different places.

SECTION IX

MAGNETIC RELATIONS OF THE CURRENT — ELECTRO-MAGNETS

289. Magnetic Field of a Current. — If a wire be bent into the form of a circle of about 20 cm. diameter and placed vertically in the magnetic meridian, and a cardboard be placed at right angles to the circle so that its

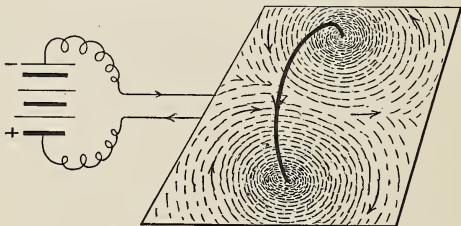


FIG. 216

horizontal diameter is coincident with the upper surface of the cardboard, and a very strong current be sent through the wire in the direction indicated by the

arrowhead in the wire, iron filings sifted upon the card will arrange themselves as shown in Fig. 216. And if a small compass be carried inside and outside the circle, the several positions taken by the needle (as indicated in the figure by arrows) show the directions of the lines of force, as indicated by the filings. If the direction of the current be reversed, the direction of the needle will be reversed wherever it may be placed. *The electric current and its encircling lines of force always coexist, and one varies directly as the other*; that is, the greater the strength of the current, the greater is the number of lines of force that occupy the field.

Fig. 217 represents the lines of magnetic force encircling a current in a straight wire. If magnetic needles be placed above and below the current, they are deflected in accordance with the rule given in § 260. It will be observed that, looking along the wire in the direction the current is flowing as indicated by the arrows, the lines of force have a clockwise direction.

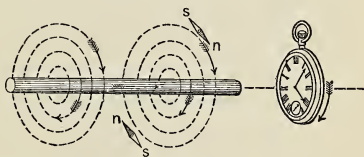


FIG. 217

290. Solenoid. — If, instead of a single circle of wire, an insulated wire be wound into a helix of several turns, it is called a *solenoid*. The intensity of the magnetic field is greatly increased by the joint action of the many current turns. The passage of an electric current through a solenoid gives it all the properties of a magnet. The resultant lines of force pass through the solenoid parallel to its axis, as shown in Fig. 218.

A solenoid encircling an iron core constitutes an *electro-magnet*. By reason of its permeability the iron core greatly increases the number of lines of force which pass through the solenoid. Hence, the magnetic

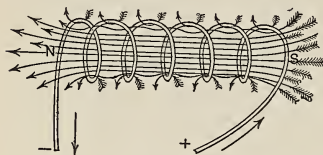


FIG. 218

strength of a solenoid is greatly increased by the presence of an iron core.

291. Polarity of an Electro-Magnetic Solenoid. — Fig. 219 repre-

sents a small voltaic cell floating on water. The leading-out wire of the cell is wound into a horizontal solenoid. Slowly, after the cell is floated, it will take a position

so that the axis of the solenoid will point north and south like a magnetic needle. Hold the *S*-pole of a bar magnet near that end of the solenoid

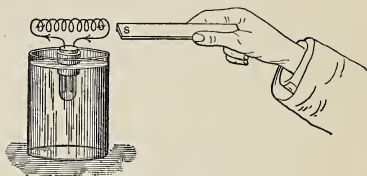


FIG. 219

which points north; the solenoid is attracted by the magnet. Hold the *N*-pole of the magnet near the north-pointing end of the solenoid; the magnet repels the solenoid.

We thus prove that a solenoid bearing a current possesses polarity as if it were a magnet, and that there can be produced by a current-bearing solenoid a magnetic field of the same character as that produced by a permanent magnet. There is no essential difference

between a permanent magnet, a current-bearing solenoid, and an electro-magnet, except that the last may be made much stronger than either of the others.

292. Given the Direction of the Current in a Solenoid, to find the *N*- and *S*-Poles of the Solenoid. — By placing a magnetic needle near one of the poles of a current-bearing solenoid the pupil should verify the following rule: Place the palm of the right hand against the side of the solenoid so that the fingers will point in the direction of the current passing through the windings (as shown in Fig. 220); the thumb will point in the direction of the *N*-pole of the solenoid or electro-magnet.

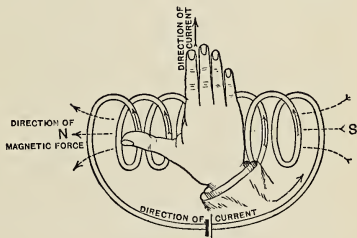


FIG. 220

Fig. 221 represents the two poles of a U-shaped electro-magnet, and shows the method in which the wire is wound in the two helices and the relative direction of the current in the same. It will be seen that the *S*-pole is that about which the current flows in the direction in which the hands of a clock move, while that is the *N*-pole about which the current has an anti-clockwise motion. Evidently, if the current be reversed, the polarity will be reversed.



FIG. 221

SECTION X

ELECTRO-DYNAMICS

293. Mutual Action between Currents. — Fig. 222 represents a portion of a divided circuit. The lower ends of the wires dip into mercury about $\frac{1}{16}$ of an inch, and the wires are so suspended that they are free to move toward or from each other. Send the current through this divided circuit; the two portions of the current travel in the same direction and parallel to each other, and the two wires at the lower extremities move toward each other, showing an attraction.



FIG. 222



FIG. 223

Make the connections (Fig. 223) so that the current will go down one wire and up the other. They repel each other.

The force manifested in either the attraction or the repulsion is called an *electro-dynamic force*. We shall find that this force may cause a variety of motions; that it is the foundation of the motive power by which electric cars are propelled and innumerable kinds of mechanical work are performed. The laws which govern these motions, therefore, demand our somewhat careful attention.

From what we learned in § 289 it is apparent that the flux paths (or lines of force) in the first case given above have directions as represented in Fig. 224. The wires in this case approach each other; in other words,

the motion of the conductors of electricity is such as to cause them to be encircled by as much flux as possible. Fig. 225 represents the directions of the flux paths in



FIG. 224



FIG. 225

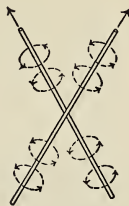


FIG. 226

the second case. In this case the flux paths are oppositely directed and the two conductors tend to separate.

Fig. 226 represents sections of two current-bearing wires which are free to move. From what we have just learned respecting the tendency of currents to place themselves so as to be enveloped by as much flux as possible having a common direction, we can see that these wires will close up like a partially opened pair of scissors. In other words, *angular currents tend to become parallel*.

The mutual action between currents was discovered by Ampère in the year 1821.

294. Ampère's Laws. — **LAW 1:** Parallel currents in the same direction attract one another; parallel currents in opposite directions repel one another.

LAW 2: Currents that are not parallel tend to become parallel and to flow in the same direction.

Fig. 227 represents a very simple motor constructed on the principle of the first of the above laws. A current sent through

the spiral wire flows nearly parallel to itself, and the attraction between the several turns of wire causes the coil to contract lengthwise. This lifts the lower end of the wire out of a cup of

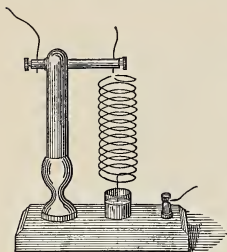


FIG. 227

mercury below; but the instant it leaves the mercury the circuit is broken, the current and attraction cease, and the wire dips into the mercury again. Thus, a vibratory motion of the coil is produced.

295. Other Illustrations of Electro-Dynamical Action. — Recalling the fact that a magnetic needle has flux lines issuing from its *N*-pole and entering its *S*-pole, and keeping in mind the principles discussed, it will be seen that

when a magnetic needle is placed over (or under) a current-bearing wire with its axis parallel to the wire, as in Fig. 228, it will tend to turn (or, if movable, the wire will tend to turn) and take a position at right angles to the wire, so that both wire and needle may be invested by a large amount of magnetic flux having a common direction. To accomplish this the needle must turn in a definite direction.

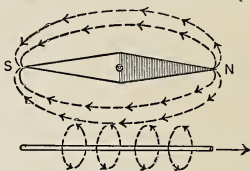


FIG. 228

Again, on examination of Fig. 229 we find that the directions

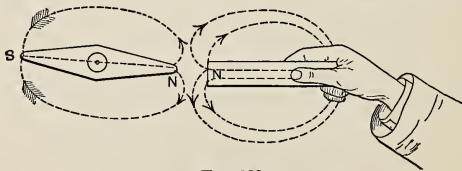


FIG. 229

of the two sets of flux paths about the two magnets bear the same relation to one another as those represented in Fig. 225 encircling

the two conductors; consequently, we expect that when like poles of two magnets are brought into proximity they will repel each other.

Electro-dynamical action will be further discussed in Section XIII, under the title of The Electric Motor.

SECTION XI

PRODUCTION OF ELECTRIC CURRENTS BY INDUCTION

This field was first entered upon by Faraday in 1831, and his investigations constitute an epoch in the history of electrical science.¹

296. Description of the Induction Coil. — This apparatus may be defined as a device for transforming an ordinary current from a voltaic battery which is of comparatively low potential into one of greatly increased potential, though of reduced strength. It consists of two coils of insulated copper wire. Coil *A* (Fig. 230), called the *primary*, is composed of short coarse wire, and therefore is of low resistance. Coil *B*, called the *secondary*, is composed of long fine wire, and its resistance is large. Coil *A* is in circuit with a voltaic cell which furnishes the primary or inducing current. Another independent circuit, having in it no cell or other generator, contains coil *B* and a sensitive galvanometer, *G*.

Experiment 1. — Lower the primary coil quickly into the secondary coil, watching at the same time the needle of the galvanometer to see whether it moves, and, if so, in what direction.

¹ The discovery of induced currents (1830) by Joseph Henry of our own country really preceded Faraday's; but as Henry was anticipated in the date of publication, the priority is usually given to Faraday.

Simultaneously with this movement there is a movement of the needle, showing that a current must have passed through the secondary circuit. Let the primary coil rest within the secondary. The needle will come to rest at zero, showing that the secondary current was a temporary one. Now, watching the needle, quickly pull the primary coil out; another deflection occurs, but in the opposite direction, showing that a current in the opposite direction is caused by withdrawing the coil.

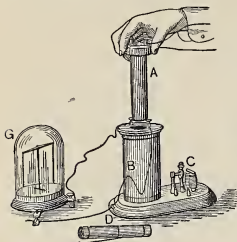


FIG. 230

It is evident that in this case the current does not by its mere presence cause an induced current, but a *change in the relative positions of the two circuits*, one of which bears a current, is necessary.

Instead of a current-bearing coil, a bar magnet may be introduced into the secondary coil and afterwards withdrawn from it. The needle is deflected at each act, as before.

Experiment 2. — Open the primary wire at some point and place the primary coil within the secondary.

On closing the circuit (Fig. 231), by bringing into contact the terminals, a deflection is produced. As soon as the needle becomes quiet, break the circuit by separating the terminals; a deflection in the opposite direction occurs.

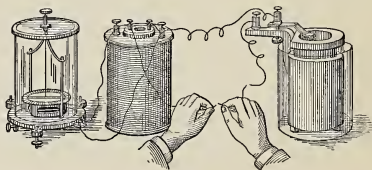


FIG. 231

The same phenomena occur when the primary is by any means suddenly *strengthened* or *weakened*. The

act by which the primary, or a magnet, causes a current in a neighboring secondary is called *induction*.

297. Faraday's Law of Induction. — When, by any means whatever, the total number of lines of force inclosed by a circuit is changed, an electric current proportional to the rate of change is produced in that circuit. The current so produced is called an *induced* current.

298. Self-Induction; Extra Currents. — When any voltaic circuit is broken at any point, at that instant there may be seen at that point (especially in a darkened room) a minute spark. The explanation is as follows: As long as a current traverses a conductor it is invested by lines of magnetic force, but when the

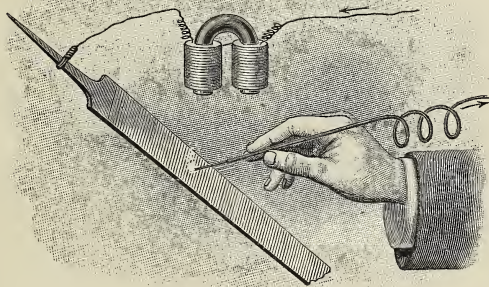


FIG. 232

circuit is broken these lines suddenly vanish, thus producing, as explained above, an induced current in the selfsame circuit. It is this induced current, commonly called an *extra current*, which as it passes between the terminals produces the spark. Extra currents become quite intense, and the sparks correspondingly brilliant when a helix, or preferably an electro-magnet, is placed

in the circuit. Thus, if one of the electrodes of a circuit containing an electro-magnet (Fig. 232) and a voltaic cell be attached to a file and the other electrode be drawn along the file, the current is started and stopped as each ridge is crossed and a series of bright sparks is observed. On this principle are constructed so-called "sparkers" for lighting gas. In this case automatic interrupters are used like those of induction coils. (See § 299.)

299. Ruhmkorff Coil. — A core, best made of a bundle of iron wires (*AA*, Fig. 233), inserted into the primary coil, greatly increases the number of lines of force or the magnetic flux about

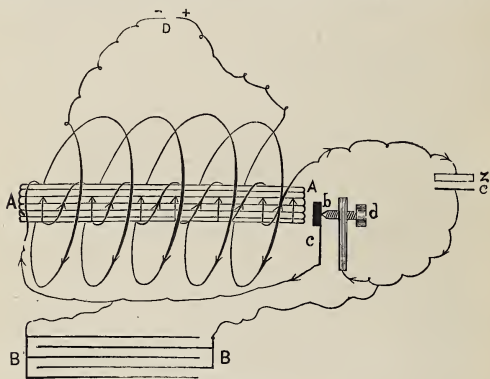


FIG. 233

the coil and, consequently, greatly intensifies the secondary currents. The intensity of these currents is further increased by the addition of a so-called condenser, *BB*. Coils which have condensers are called *Ruhmkorff coils*, in courtesy to the inventor of this attachment.

In coils of this kind the primary remains permanently within the secondary, and the "make and break" method of inducing currents is employed. To save the trouble of making and breaking by hand, as described in Experiment 2, the core is utilized in



MICHAEL FARADAY (1791-1867)

Eminent as a scientific investigator and as a lecturer. Especially notable are his investigations in *electrolysis*, in *electrical induction*, and in *electro-magnetism*. Portrait after painting by Thomas Phillips, in National Portrait Gallery, London.

the construction of an automatic interrupter. A soft-iron hammer, *b*, is connected with the steel spring *c*, which is in turn connected with one of the terminals of the primary wire. The hammer presses against the point of a screw, *d*, and thus, through the screw, closes the circuit. But when a current passes through the primary wire the core *AA* becomes magnetized, draws the hammer away from the screw, and breaks the circuit. The circuit broken, the core loses its magnetism, and the hammer springs back and closes the circuit again. Thus, the spring and hammer vibrate, and open and close the primary circuit with great rapidity.

Every make and every break of the primary is accompanied by a transitory current in the secondary, but in alternating directions. If the secondary wire be open at some point, as at *D*, a rapid succession of sparks will pass between the terminals.

Secondary currents developed in high-resistance coils have, of necessity, vastly greater E.M.F. or power to overcome resistances than the primary currents which circulate in low-resistance coils. Secondary coils have been made containing wires over 200 miles long. Such coils have produced sparks in open air 40 inches in length.

Fig. 234 represents a Ruhmkorff coil in perspective. It has in the secondary circuit a glass tube, *A*, partially exhausted of air and known as a *Geissler tube*, from its inventor. Platinum wires are sealed into the glass at each end of the tube to conduct the electric current through the

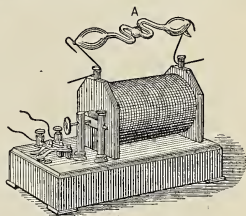


FIG. 234

glass. As the current passes through the vacuous space, the entire tube becomes illuminated with a continuous glow.

300. The Transformer.—An induction coil is in a certain sense a reversible machine. If a current of considerable strength circulate under small E.M.F. in the primary, then variations in its strength give rise to very weak currents of exceedingly high E.M.F. in the secondary. Conversely, if we cause weak currents

under very high E.M.F. to circulate in the *secondary*, by their fluctuations there will be generated in the primary strong currents of small E.M.F. We do not in either case create electric energy. Electric power is the product of two factors, current and electro-motive force. The induction coil enables us to increase one of these factors at the expense of the other. The *transformer* — sometimes called a converter — is merely an induction coil used to change the relation of the number of volts to the number of amperes of any current. In a *perfect* transformer the number of watts in the primary is equal to the number of watts in the secondary.

Transformers are used when currents of high voltage are to be carried great distances and delivered at a pressure that is safe to handle. With a great resistance in the line, due to its length or diminutive size, the loss in watts is less with a current of few amperes and high voltage than it is with a strong current and low voltage. Hence, high-voltage currents enable us to use smaller copper wires. The chief advantage, therefore, to be derived from high-voltage currents in transmitting electrical power long distances, as for example from Niagara Falls to the city of Buffalo, is economy of power and of copper, which is expensive. Currents generated by an alternating dynamo of 30,000 volts may be transmitted a distance of 50 miles over comparatively small wires, and be transformed into currents that are perfectly safe for domestic purposes.

SECTION XII

DYNAMO-ELECTRIC MACHINES

301. Principles of the Dynamo. — The dynamo, like the voltaic cell, is a device for generating electric currents. The fundamental phenomenon involved in the construction of all dynamo machinery is that of the *induction of currents*, discovered by Faraday. The dynamo

embraces a system of coils which are made to move in a magnetic field in such a way that the number of lines of magnetic flux passing through them varies continuously. As we have previously learned, this creates a difference of potential in the system, so that if the points of different potential be connected by a wire, a current will be established in the circuit.

The magnetic flux through a coil may be changed in two ways: either (1) by moving the coil through a field in which the density of the lines of force varies, as represented in Fig. 235; or (2) by causing the plane of the

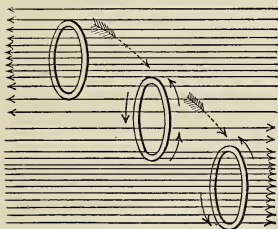


FIG. 235

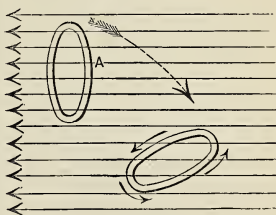


FIG. 236

coil to revolve so as to change the angle which it makes with the lines of flux, thus varying the number inclosed, as represented in Fig. 236.

302. Construction and Operation of the Dynamo.—The two essential features of the dynamo are: (1) the *magnetic field* and (2) the *armature*, that is, the movable coil or series of coils so arranged as to cut the lines of flux. The inducing or field magnet may be either a permanent steel magnet or an electro-magnet, preferably the latter, as with it a much stronger field can be obtained.

A machine is called a *magneto* (see Fig. 240) when the field is produced by a permanent magnet and a *dynamo* when it is produced by an electro-magnet.

The simplest form of generator consists of a loop of wire, *AB* (Fig. 237), arranged so as to be rotated between



FIG. 237

the poles of a magnet. The loop of wire in its present position incloses the largest possible number of flux lines. As it rotates from this position, as indicated by the arrow

over the loop, the number of lines of flux that pass through the loop constantly diminishes until a quarter of a turn is completed. At this point no lines pass through the loop. From what we have hitherto learned, it is apparent that during this quarter of a turn a current will circulate in the loop in the direction indicated by the arrows. During the next quarter turn the lines will increase, but they will pass through the loop from the opposite side, so that there is no change in the direction of the current in this quarter turn. But after a half turn is completed, and during the third quarter turn, the lines decrease and their direction through the loop is the same as during the second quarter turn; consequently, the direction of the current is reversed. The current is, therefore, reversed twice in every revolution, giving rise to what is called an *alternating current*. The loop of wire in which currents are induced is the *armature*. In ordinary dynamos this simple loop is replaced by a coil of many turns of wire embracing an iron core.

On the axle of the armature are two rings of metal, *a* and *b* (Fig. 238), which are insulated from each other.

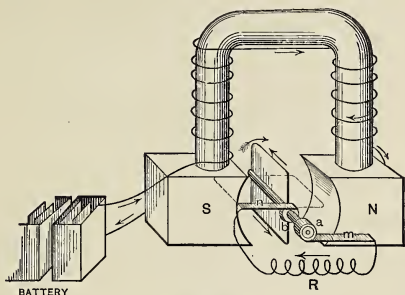


FIG. 238

Resting on these rings are metallic springs or pieces of carbon, *n* and *m*, called *brushes*. The terminals of the loop are connected with these brushes. When the armature is rotated one of these rings will always be at a higher potential than the other, but there can be no current because they are insulated from each other. By connecting the two brushes, however, by a leading-out wire, *R*, just as we connect the elements of a voltaic cell, we establish an “external circuit,” through which the induced currents flow, as in a voltaic circuit.

303. The Commutator. — The alternating current is not adapted to all uses, and for many purposes it is necessary to have the current continuously flowing in the same direction. To accomplish this a *commutator* is attached to the axis of the armature. In this case the two metal rings on the axle are replaced by two halves of a split ring or tube. Fig. 239 represents the axle

and commutator, in which A and B are the segments of the ring. These segments are insulated from each other. The terminals of the armature coil, E and F , are connected with these segments, and the brushes C and D press upon the opposite segments. The connecting wire, R , constitutes the external circuit. The two brushes exchange connections with the segments at the same instants that the current in the armature reverses, so that brush C is always positive and brush D is always

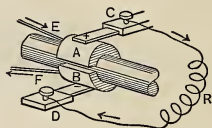


FIG. 239

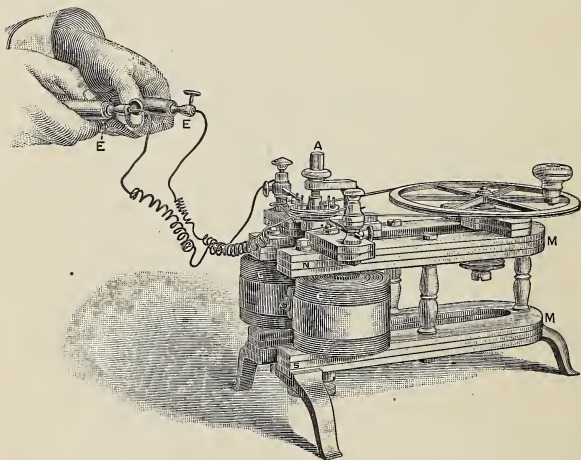


FIG. 240

negative. Hence, the current through the external circuit R is constantly in the same direction. Such a dynamo is called a *direct-current dynamo*.

Fig. 240 represents a simple form of *magneto-electric machine* which has long served a useful purpose in simple lecture-room demonstrations. It is the progenitor of all machines that have been contrived for transforming mechanical into electrical energy. *CC* are two armature coils which revolve about the axle *A*, between the opposite poles, *N* and *S*, of two compound U-magnets, *M* and *M*. *E* and *E* are two electrodes which are held in the hands in order to cause the current to pass through the human body.

304. E.M.F. of a Dynamo.— This depends upon (1) *the rapidity of motion of the armature*; (2) *the number of coils of wire in the armature connected in series*; and (3) *the number of lines of magnetic flux cut per second, or the strength of the field*.

305. Commercial Efficiency of a Dynamo.— It is apparent that mechanical energy must be expended in maintaining the motion of the armature. The dynamo is, in fact, a machine for transforming mechanical into electrical energy.

The commercial *efficiency* of a dynamo is the ratio of the useful electric power developed in the external circuit to the mechanical power expended in turning the armature. In general, its efficiency is very high, — in the best machines 90 per cent or more.

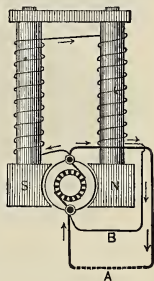


FIG. 241

306. Classification of Dynamos.—Dynamos may be classified according to the method by which their field magnets are excited. Fig. 238 illustrates what is called a *separately excited* dynamo, where the field-magnet coils receive their current from a separate generator, *e.g.*, a battery.

Fig. 241 illustrates a *shunt machine*, where the field coil serves as a shunt to the external circuit. *A* is the main wire and *B* is the shunt wire. In the shunt machine a part of the current generated in the armature passes through the coils of the field magnet and thus excites it. A dynamo is said to be “self-exciting” when the whole or any part of the current which is produced is used to generate the field.

The cores of the field magnets of a self-exciting dynamo, after being once excited from any source, *e.g.*, another dynamo, always

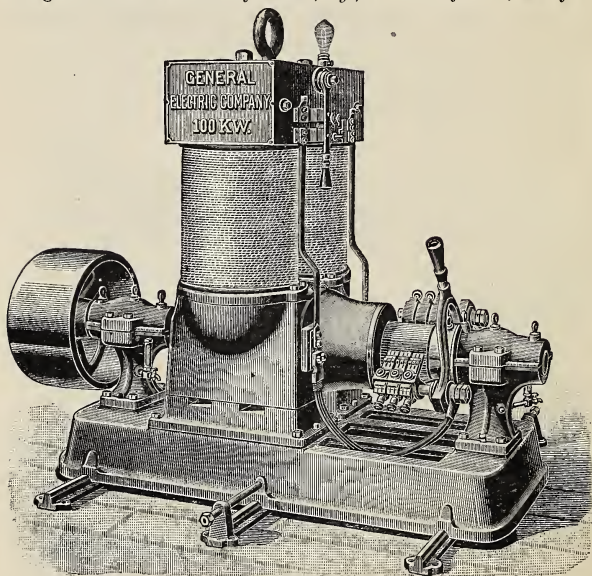


FIG. 242

retain a little residual magnetism, so that when the armature begins to rotate a slight current is at once induced in it. This current strengthens the field, and the stronger field reacts to

increase the current, so that the current soon rises to its normal strength.

All figures hitherto have been diagrammatic representations of dynamos. Fig. 242 represents in perspective a form of the Edison dynamo. It is a shunt-wound machine.

SECTION XIII

ELECTRO-DYNAMICS CONTINUED—THE ELECTRIC MOTOR

307. Motion produced by Electro-Dynamic Forces.—Let AB (Fig. 243) represent a current-bearing loop free to rotate about an axle, CD . It is placed in a field of magnetic flux, *e.g.*, between poles of a magnet. Now the action of the electro-dynamic forces between the field flux and the flux which encircles the current-bearing loop is such as to cause the loop to move from the position AB to the position $A'B'$. In other words, *the loop always tends to move into such a position as to enable it to include the largest possible number of flux lines.*

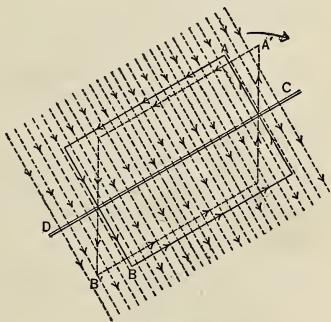


FIG. 243

If, when the loop reaches the position $A'B'$, the direction of the current in the loop is reversed by means of a commutator on the axle CD , the loop will continue its motion in the same direction. A machine by means of

which electric energy is transformed into mechanical energy through the instrumentality of electro-dynamic forces is called an *electric motor*.

308. Reversibility of the Dynamo. — It cannot have escaped the notice of the reader that the mechanism of the motor is the same as that of the dynamo. Almost any dynamo may be used as a motor, *i.e.*, to transform energy of electric currents into mechanical work. In such usage the armature, instead of being the source of a current, is supplied with a current from some external source, such as a voltaic battery or another dynamo. If, for example, two dynamos be connected by wires in the same circuit and the armature of one be rotated, the armature of the other will rotate as soon as the current transmitted from the first attains a certain intensity.

Let *A* and *B* (Fig. 244) represent in diagram two dynamos constructed exactly alike. Mechanical power is supplied to the

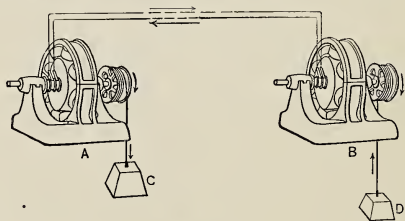


FIG. 244

dynamo *A* by the falling weight *C*. In this dynamo mechanical energy is transformed into the energy of an electric current, which in passing through *B* (now acting as a motor) becomes again transformed into mechanical energy which raises the weight *D*.

The energy stored in D after it is raised, plus some additional energy to compensate for that lost in the transmission from A to B and in the several transformations, may be used again by a reversal of transformations to raise the weight C .

309. The Electric Railway.—The system of electric-car propulsion consists in the generation of an electric current at some power station by means of dynamos, its transmission over conductors to the electric motors on the cars, and its transformation into mechanical energy, which gives motion to the car.

SECTION XIV

SECONDARY OR STORAGE CELLS — THERMO-ELECTRIC BATTERIES

310. Secondary Currents.—After decomposing an acid solution for a brief time between the platinum electrodes in an electrolytic cell (see § 258), if you replace the battery by a sensitive galvanometer, a deflection of the needle shows that a current opposite to that which previously flowed in the circuit is now produced by the electrolytic cell. This current is produced as follows: The platinum electrodes during the electrolytic action become polarized, and energy is thus stored in the electrolytic cell. Polarization is of the nature of a counter E.M.F. It is precisely this polarization which we have to contend with in nearly all voltaic cells, and which we seek to neutralize by means of depolarizing agents.

Devices for thus storing energy by electrolysis are called *storage* or *secondary cells*, and sometimes *accumulators*. Note that the process is an *electrical storage* of

energy, not a storage of electricity. The energy of the charging current is transformed into the potential energy of chemical separation in the storage cell. When the circuit of the storage cell is closed, this energy is reconverted into the energy of an electric current in precisely the same way as with an ordinary voltaic cell.

The storage battery offers a means of accumulating energy at one time or place and using it at some other time or place. For example, energy of a dynamo current may be stored during the daytime when the current is not needed for illuminating purposes; and this energy, reconverted into electric energy, may feed incandescent lamps at night at any convenient place; or the charged cells may be transported to lecture halls, workshops, electric cars, etc., where powerful currents may be needed.

An efficient form of storage cell in which the plates are made of lead and lead oxides has an E.M.F. of 2.2 volts or more. Its resistance depends on the size and number of plates, but is often not greater than .005 ohm; consequently, the current which it yields is very much stronger than that of any ordinary galvanic cell.

311. Thermo-Electric Batteries.

Experiment. — Let *G* (Fig. 245) be a very sensitive galvanometer. Form two junctions between its copper-wire terminals and

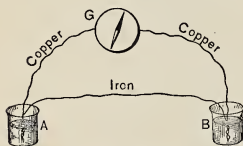


FIG. 245

an iron wire by tightly twisting the wires together near their extremities. Let *A* and *B* be the two junctions. Immerse both junctions in separate beakers of water. (1) Raise the water in one of the beakers to the boiling point; a current passes through the galvanometer *G*, causing a deflection.

(2) Reverse the position of the two beakers of water; the current now causes a reversed deflection. (3) Bring the cold water to the boiling point; the deflection diminishes steadily to zero as thermal equilibrium is established.

Thus, the thermo-electric current depends on the difference of temperature of the junctions, vanishing when that difference vanishes. Suppose the junctions to be at 10°C. and 100°C. ; the E.M.F. will be about 0.0015 volt. It would require about 1000 pairs of such junctions to give an E.M.F. comparable to that of an ordinary voltaic cell.

The E.M.F. may be increased by combining a large number of pairs with one another in series. This is done on the same principle and in the same manner that voltaic cells are united, that is, by joining the + electrode of one to the - electrode of another. Fig. 246 represents such an arrangement. The light bars are bismuth and the dark ones antimony. If the difference of temperature of the two faces be made very great, an E.M.F. may be obtained as great as that of a voltaic cell. Such contrivances for generating electric currents are called *thermo-electric batteries*. They are seldom used because of their low E.M.F., and because the best of them transform less than 1 per cent of the heat energy employed. They are of interest to us chiefly because they demonstrate the fact that *heat energy may be directly transformed into electric energy*.

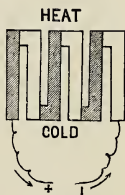


FIG. 246

SECTION XV

THE ELECTRIC LIGHT

312. Electric Light; Voltaic Arc. — If the terminals of a powerful dynamo or galvanic battery be brought together, and then separated 1 or 2 mm., the current does not cease to flow, but volatilizes a portion of the terminals. The vapor formed becomes a conductor of

high resistance and, remaining at a very high temperature, produces intense light. The heat is so great that it fuses the most refractory substances. Metal terminals quickly melt and drop off like tallow and thereby



FIG. 247

become so far separated that the electro-motive force is no longer sufficient for the increased resistance, and the light is extinguished. Hence, pencils of carbon, being less fusible, are used for terminals. The larger portion of the light emanates from the tips of the two carbon terminals which are heated to an intense whiteness. The light is too intense to admit of examination with the naked eye, but if a pin-hole image of the terminals be thrown upon a screen, an arch-shaped light, known as the *electric arc*, is seen extending between the terminals. This is due to the transfer of light-

giving particles of carbon from the positive to the negative electrode. What we see is not electricity, but a *luminous cloud of matter*.

The terminals are slowly consumed by combustion; at the same time a conical-shaped cavity, called the *crater*, is formed at the positive terminal, while the negative terminal becomes conical (Fig. 247). When, in consequence of combustion, the distance between the two pencils becomes too great for the electric current

to span, the light goes out. Numerous self-acting regulators for maintaining a uniform distance between the carbons have been devised. Such an arrangement (Fig. 248) is called an *electric lamp*. The movements of the carbons are produced automatically by the action of the current itself.

313. Incandescent Electric Lamps.—The incandescent or “glow” light is produced by the heating of some refractory body to a state of incandescence by the passage of an electric current (see § 262). Carbon filaments are generally used in incandescent lamps. It is essential that the oxygen of the air be removed from these bulbs to prevent the carbons from being quickly burned; hence, very high vacua are produced in the bulbs.

Fig. 249 represents such a lamp. The loop or filament of carbon *L* is joined at *nn* to two platinum wires which pass through the closed end of the glass tube *T*. One of these wires is connected with the brass ring *B*, and the other with the brass button *D*, at the bottom of the lamp. When the lamp is screwed into its socket, connection is made with the line through pieces of brass in the socket, which are insulated from each other.

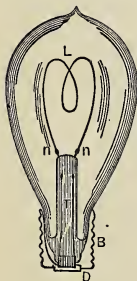


FIG. 249

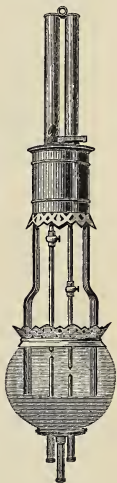


FIG. 248

An ordinary 16-candle-power lamp has a resistance (when hot) of about 140 ohms; the difference of potential at its terminals is about 110 volts, and it requires a current of 0.75 ampere.

Each lamp consumes about $\frac{1}{16}$ of a horse-power, or about 4 watts per candle-power. One kilowatt (1 k.w. \approx 1.34 h.p.) will supply nearly sixteen 16-candle-power lamps.

Fig. 250 represents an electric-light system in which *D* is an alternator dynamo, *H* high-pressure mains, *T* and *T'* transformers, *L*

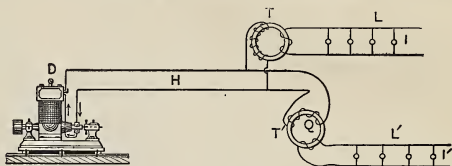


FIG. 250

L and *L'* low-pressure mains, and *I* and *I'* incandescent lamps connected in multiple.

SECTION XVI

ELECTROTYPING AND ELECTROPLATING

314. Electrotyping. — This book is printed from electrotypes plates. The matter is first set up in common type from which an impression, or mold, is made in wax. In the mold the elevations appear as depressions, and *vice versa*. The mold is then coated with plumbago to render it a conductor, and is suspended as a kathode in a solution of copper sulphate. A copper plate is used for the anode, and the whole is placed in circuit with a low-voltage dynamo. The copper sulphate is decomposed by the electric current, and the copper is deposited on the surface of the mold. The sulphuric acid appears at the + electrode and, combining with the copper of this electrode, forms new molecules of copper sulphate. When the copper film has acquired about the thickness of an ordinary visiting card it is removed from the mold. This film shows distinctly every line of the types or engraving. It is then backed with type metal to give it firmness. The plate is next fastened on a block and thus built up type high; it is then ready for the printer. (For full directions which will enable a pupil to produce electrotypes of medals, etc., in a small way, see the author's *Physical Technics*.)

315. Electroplating. — The distinction between electroplating and electrotyping is that with the former the metallic coat remains permanently on the object on which it is deposited, while with the latter it is intended to be removed. The processes are, in the main, the same. The articles to be plated, after being thoroughly cleaned, are made the kathode of a battery, and a plate of the kind of metal to be deposited is made the anode. The bath used is a solution of a salt of the metal to be deposited. Solutions of the cyanides of gold and silver are used for gold plating and silver plating respectively.

SECTION XVII

SOME ELECTRICAL APPLIANCES FOR THE TRANSMISSION OF SIGNALS

316. The Electric Bell. — When the electric circuit is closed, pressure on a push button, *P* (Fig. 251), causes a current to pass through the electro-magnet *MM*. This magnet on being excited attracts the armature *A* and causes the hammer *H* to strike the bell *B*. To the armature is attached a spring, *S*, which ordinarily presses lightly against a contact screw, *C*. The current passes along this spring to the contact screw, but when the armature is drawn away the circuit is broken. The circuit broken, *M* loses its attractive force, and *A* springs back and closes the circuit again, and the whole process is repeated many times or as long as you press on the button. The whole constitutes an automatic interrupter such as shown in Fig. 233.

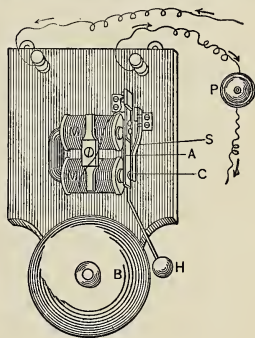


FIG. 251

317. The Electric Telegraph. — Fig. 252 represents in diagram a complete equipment of telegraphic apparatus for two stations

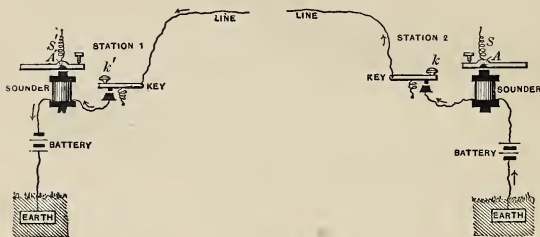


FIG. 252

that are not so far apart as to require relays.¹ First it must be understood that the earth forms a part of the circuit, so that only one wire connects the two stations. The terminals of this wire are connected either with metallic plates buried in the earth or, better, with water or gas pipes that lead to the earth. The apparatus required at each station is, as shown in the diagram, a *key*, which is used in sending messages; a *sounder*, which is the receiver; and a portion of the *battery*, which is usually divided equally between the two stations.

Every one who has ever visited a telegraph station has probably heard the clicking sounds of the receiver and is aware that the trained ear of the operator is able to decipher therefrom the message. It answers our purpose to learn how these sounds are produced simultaneously in both offices. The circuit is closed at all times when not in use. An operator at Station 1, we suppose, moves a switch (not shown in the diagram) connected with the key and thus opens the circuit at the key. He then presses down on the knob *k'* and closes the circuit for an instant. At this instant a current fills the circuit, and the electro-magnets of the sounders in both stations attract the armatures *A* and *A'* and

¹ For description of relays and for fuller treatment of telegraphy, see the author's *Elements of Physics*.

produce a click. Next the operator allows the lever of the key to be pushed up by a spring, and thus the circuit is again broken. At this instant the electro-magnets lose their magnetism; and the armatures, pulled away by springs S' and S , striking screw points above, produce another click.

318. The Telephone. — A section of a Bell telephone receiver is shown in Fig. 253. It consists of a steel magnet, A , inclosed in a vulcanite case. A coil of fine wire, B , incloses one end of the magnet, the ends of the wire, CC , being connected with the screw cups, DD . About a millimeter from the end of the magnet is clamped a thin iron disk, EE .

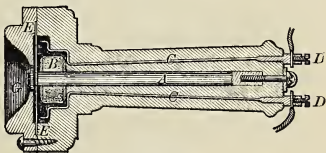


FIG. 253

An instrument constructed in precisely the same manner may be used, and originally was used, for a transmitter. The magnet magnetizes by induction the disk, and the disk reacts on the magnet, the amount of reaction being dependent on the distance between the two. When the instrument is spoken into at G the disk is made to vibrate in unison with the air vibrations, and by its to-and-fro motion the disk causes the strength of the magnet to vary. The fluctuating strength of the magnet is, of course, attended by a variation in the number of flux lines passing through the coil B ; hence, a series of induced currents is produced in the circuit of which the coil is a part. These induced currents traverse the coil of another instrument of the same kind, which is used as a receiver, and produce changes in the magnetization of the magnet in this instrument. The fluctuations in magnetism of the magnet in the receiving instrument cause the disk of this instrument to repeat whatever motions are imparted to the transmitting disk. The vibrations of the receiving disk generate sound waves corresponding to those incident upon the transmitting disk.

SECTION XVIII

RÖNTGEN PHENOMENA — HERTZIAN WAVES — MAXWELL'S THEORY OF LIGHT

319. Kathode Rays. — If a glass tube, into the opposite ends of which two wires are sealed, be exhausted to approximately one millionth of an atmosphere and the high pressure discharge of an induction coil be passed through it, many interesting phenomena occur which were investigated by Crookes and described by him in 1879.

The comparatively few remaining particles of gas in the tube are attracted like so many pith balls to the *kathode*, or negative terminal, whence, after becoming electrified, they are driven off in straight lines with a velocity computed to be not less than 25,000 miles per second. On account of the rarity of the gas these excited particles dart through the tube with comparatively few collisions, and they assume properties so novel as to justify the application of the term *radiant matter*, first applied by Faraday. These streams of radiant matter, now commonly called *kathode rays*, are capable of turning a light paddle wheel placed in their paths within the tube.

320. Röntgen Rays. — Where these charged particles strike any solid, for instance the side of the tube, the molecular impacts become the origin of a new kind of radiation that possesses some remarkable properties quite unlike, in many important particulars, those of any radiation which we have hitherto considered. The best

authorities declare that this radiation does not consist of streams of flying particles of matter, but of disturbances in the ether.

In the year 1895 Prof. W. K. Röntgen, of Würzburg in Bavaria, discovered that this non-luminous radiation emanating from a Crookes tube, even after passing through certain substances, such as cardboard, wood, flesh, aluminum, and many other substances which are quite opaque to ordinary light waves, is capable of affecting a photographic plate beyond. Not knowing the nature of the new rays, Röntgen modestly called them the *X-rays*; but they are more appropriately called the *Röntgen rays*.

The fact that flesh is comparatively transparent and bone comparatively opaque to these rays makes it possible to make radiographs of the living skeleton, the resulting negatives being of the nature of shadow pictures. When we add that most metals are rather opaque to these rays, it is easy to see how radiographs of foreign bodies imbedded in the flesh, such as needles, bullets, etc., may be obtained, and how radiography may be of immense value to surgery in locating these bodies with precision.

A sensitive plate is inclosed in an envelope of black paper, so as to exclude all light from the plate. The hand, for example, is placed flat on the plate and a properly constructed Crookes tube is fixed 1 or 2 feet above it. When the tube is excited by an induction coil or other



FIG. 254

suitable apparatus those Röntgen rays that meet only flesh pass with little loss through it and the paper to the plate, while those that meet bone are largely obstructed; hence, a shadow outline of the hand is pictured upon the plate, the bones appearing darker than the flesh, while such an opaque object as a gold ring casts a very dark shadow.

Fig. 254 represents a shadowgraph, or radiograph, of a hand wearing a ring. Fig. 255 represents the apparatus during the operation of taking a radiograph of a hand. The current for this purpose may be taken from a storage battery or from a street electric-light wire.

There is a fundamental difference between the methods of ordinary photography and those of radiography. In the latter no lenses are used for focusing, since up to the present time no

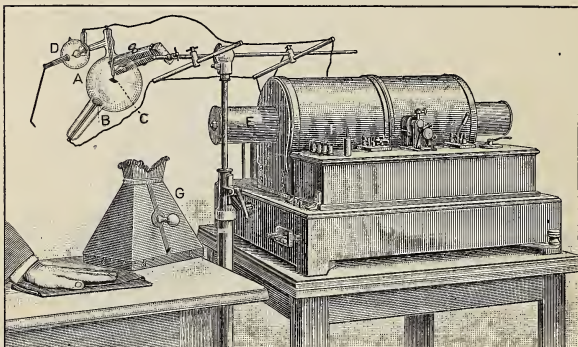


FIG. 255. — *A* is the Crookes tube; *B*, the cup-shaped cathode made of aluminum; *C*, the anode made of platinum, whence emanate the Röntgen rays; *D*, a supplementary tube which regulates automatically the degree of exhaustion within the tube *A*; *E* and *F*, the primary and secondary coils, respectively, of a Ruhmkorff coil; *G*, a fluoroscope.

means of refracting Röntgen rays has been discovered; consequently, the picture produced is merely a record of the shadows cast by the bones.

321. Fluoroscope. — A very important accessory to the apparatus described above is an instrument called a *fluoroscope*. It consists of a box (Fig. 256), dark in the interior, with an opening at the small end, into which to look. At the opposite and larger end is spread some fluorescent material,¹ preferably barium platinum cyanide. Any body that is opaque to Röntgen rays, if placed outside the fluorescent screen, and between it and the Crookes bulb, casts upon the screen a shadow which may be viewed by looking in at the opening. For example, one can see a shadow picture of the bones of his own hand upon the screen which is elsewhere fluorescent.



FIG. 256

In order to obtain a fluorescent picture of the chest of a human being, you would place an excited tube at his back (it is not necessary that the clothing be removed) and the large end of the fluoroscope close against his breast; looking in at the small end and covering this aperture with your face so as to exclude all light, you would see quite distinctly shadow pictures of the skeleton, and somewhat dimly the outlines of the moving organs, such as the heart, etc.

322. Hertzian Waves ; Wireless Telegraphy. — It has been proven experimentally that an electrical discharge such as occurs between the electrodes of the secondary coil of a Ruhmkorff coil is not, as it appears to the eye, a single passage of electricity but a multitude of to-and-fro discharges passing at the rate of many thousand per second. The discharge may be likened to the vibrations

¹ Ultra-violet rays and Röntgen rays, though invisible themselves, are capable of causing certain substances, said to be *fluorescent*, to glow when exposed to them.

of an elastic rod clamped at one end. Hence, the discharge is said to be *oscillatory*.

Hertz demonstrated (1888) the presence of ether waves radiated through space at the instants when oscillatory discharges take place. These waves are called *electro-magnetic* waves. Maxwell had declared, years before, that such waves must be generated by the action of the Ruhmkorff coil, but it remained for Hertz to devise a means of detecting them. Various devices have been employed by him and by others for this purpose, but the most efficient detector employed at present is the "coherer" invented by Edouard Branly. It consists of a glass tube, *A* (Fig. 257), filled with a carefully prepared mixture of metallic powders placed in circuit with a voltaic cell and a very sensitive galvanometer. The powder offers a very high resistance, but when an electric wave such as that described above reaches the coherer, it causes the particles of powder to stick together, or cohere, thus lessening the resistance and increasing the deflection in the galvanometer. The practical man at once sees in this the possibility of transmitting signals without the use of wires.

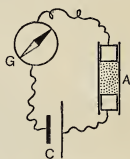


FIG. 257

Modifications of this contrivance devised by Marconi and others have recently been adopted for wireless telegraphy. The electro-magnetic waves travel with the speed of light, but unlike light waves they will pass through the walls of a building; and the recently reported signals sent across the ocean seem to indicate that even the sphericity of the earth is not an insuperable obstacle to their transmission from continent to continent.

323. Maxwell's Theory of Light. — In 1865 Maxwell propounded the theory that light is the result of electromagnetic disturbances in the ether of rapidly alternating character, such as would result from local strains and releases; and that light waves are electro-magnetic waves of a limited range of wave length.

The Maxwellian theory is now considered verified by the more recent developments and researches of Hertz and others.¹ The importance of this theory from a scientific outlook is great, inasmuch as it teaches us to refer electrostatic and electro-magnetic phenomena to the intervention of the same ether sea. It becomes more and more evident that this medium is the vehicle by which energy, manifested in a great variety of vibrations, passes through space from one body to another. The expression "radiant energy" is continually acquiring new scope in physics.

¹ See Hertz's "Researches on Electrical Oscillations," *Smithsonian Report*, 1889, or Hertz's *Electric Waves*.

APPENDIX

TABLES OF METRIC MEASURES

MEASURE OF LENGTH

1 Millimeter (mm.)	= 0.001 meter (m.)	= 0.03937 inch.
1 Centimeter (cm.)	= 0.01 m.	= 0.39371 inch.
1 Decimeter (dm.)	= 0.1 m.	= about 4 inches.
1 Meter	= 39.37079 inches	= about 3 feet $3\frac{3}{8}$ inches.
1 Kilometer (km.)	= 1000 m.	= about $\frac{5}{8}$ mile.

MEASURE OF SURFACE

1 Square millimeter (mm. ²)	= 0.000001 square meter (m. ²)	= 0.0015 square inch.
1 Square centimeter (cm. ²)	= 0.0001 m. ²	= 0.1550 square inch.
1 Square decimeter (dm. ²)	= 0.01 m. ² .	
1 Are	= 100 m. ² .	

MEASURE OF VOLUME

1 Cubic millimeter (mm. ³)	= 0.000000001 cubic meter (m. ³).
1 Cubic centimeter (cc. or cm. ³)	= 0.000001 m. ³ = 0.061 cubic inch.
1 Cubic decimeter (dm. ³)	= 0.001 m. ³ = 1000 cc.
1 Cubic meter	= about 1.308 cubic yards.

MEASURE OF CAPACITY

1 Milliliter (ml.)	= 0.001 liter (l.)	= 1 cc. = 0.061 cubic inch.
1 Centiliter (cl.)	= 0.01 l.	= 10 cc.
1 Deciliter	= 0.1 l.	= 100 cc.
1 Liter		= 1000 cc. = 61.027 cubic inches
		= 1.0567 quarts (liquid measure).

Inches



Millimeters

Centimeters



Milliliter

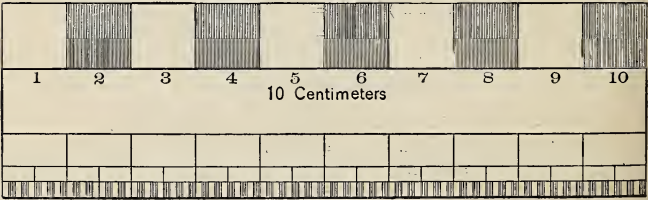


Cubic Centimeter

The area of this figure is a square decimeter.
A cube of water, one of whose sides has this area,
is a cubic decimeter or a liter of water, and at the
temperature of 4° C. has a mass of a kilogram.
The same volume of air at 0° C., and under a
pressure of one atmosphere, has a mass of 1.293 g.
The gram is the mass of 1 cc. of pure water at 4° C.

Square
Centimeter

Square Inch



10 Centimeters

100 Millimeters

MEASURE OF MASS

1 Milligram (mg.)	= 0.001 gram (g.)	= 0.0154 grain.
1 Centigram (cg.)	= 0.01 g.	= 0.1543 grain.
1 Decigram (dg.)	= 0.1 g.	= 1.5432 grains.
1 Gram		= 15.432 grains.
1 Kilogram (kg.)		= 1000 g.
		= 2.2046 av. pounds.

TABLE OF EQUIVALENT VALUES

1 inch	= 0.0254 m.	= 2.53995 cm.	= about $2\frac{1}{2}$ cm.
1 foot	= 0.3048 m.	= 30.48 cm.	= about $30\frac{1}{2}$ cm.
1 mile	= 1609 m.	= 1.609 km.	
1 square inch	= 6.4514 cm. ² .		
1 square foot	= 929.01 cm. ² .		
1 cubic inch	= 16.38618 cc.		
1 cubic foot	= 28,316 cc.		
1 U. S. quart	= 946 cc.	= 0.946 l.	
1 av. pound	= 453.59 g.	= 0.45359 kg.	= about $\frac{5}{11}$ kg.

PROPERTIES OF LIQUIDS

	Specific Gravity	Expansion Coefficient at 0°	Melting Point	Boiling Point 760 mm.	Specific Heat	Refractive Index
Acid, nitric, 0° . . .	1.5	0.00111	— 47°			
“ sulphuric, 0° . .	1.84	0.00059		330° ?	0.34	1.43
Alcohol, 0°	0.81	0.00106		78.2°	0.59	1.36
Benzine, 20°	0.87	0.00118	4°	80°	0.39	1.49
Ether, 0°	0.73	0.00148		35°	0.54	1.35
Mercury, 0° (Regnault)	13.596	0.00018	— 39°	350°	0.034	
Olive oil, 0°	0.92	0.00080				1.47
Sea water, 0°	1.026					
Water, 0°	0.999		0°	100°	1.00	
“ 4°	1.000					1.33
“ 20°	0.998					

PROPERTIES OF SOLIDS

	Specific Gravity 17° C.	Hard- ness	Expansion Coefficient 0°-100°	Melting Point	Specific Heat	Latent Heat of Fusion	Refract- ive Index
Aluminum . .	2.7	3	0.00002	700°	0.21		
Beech. . . .	0.8						
Bismuth . . .	9.8	2	0.000013	266°	0.03	13	
Boxwood . .	0.9						
Brass (cast) .	8.3	3	0.000019	900°?	0.09		
Cherry . . .	0.7						
Copper . . .	8.8	3	0.000017	1100°	0.09	30	
Cork	0.24						
Diamond . .	3.5	10			0.14		2.47
German silver .	8.5	3	0.00002				
Glass (crown) .	2.5		0.000007	400°	0.19		1.51
“ (flint) . .	3.6						1.62
Gold	19.3		0.000012	1050°	0.03		
Ice.	0.9	1.5		0°	0.5	79.7	1.31
Iron (cast) . .	7.2	6?	0.000012	1500°	0.11		
Lead	11.3	2	0.000028	326°	0.03	5	
Marble . . .	2.7	3			0.21		
Paraffine . .	0.9			55°			
Platinum (wire)	21.4		0.000008	1800°	0.03		
Quartz . . .	2.6	7					1.54
Silver. . . .	10.4		0.000019	1000°	0.05	24	
Steel (tempered)	7.8	9?	0.000013				
Tin	7.3	2	0.000019	232°	0.05	14	
Zinc	7.1	3	0.00003	360°	0.09	28.	

SPECIFIC GRAVITY OF GASES

(Standard: air at 0° C.; barometer, 760 mm.)

Air	1.0000	Hydrogen	0.0693
Ammonia	0.5367	Nitrogen.	0.9714
Carbonic acid	1.5290	Oxygen	1.1057

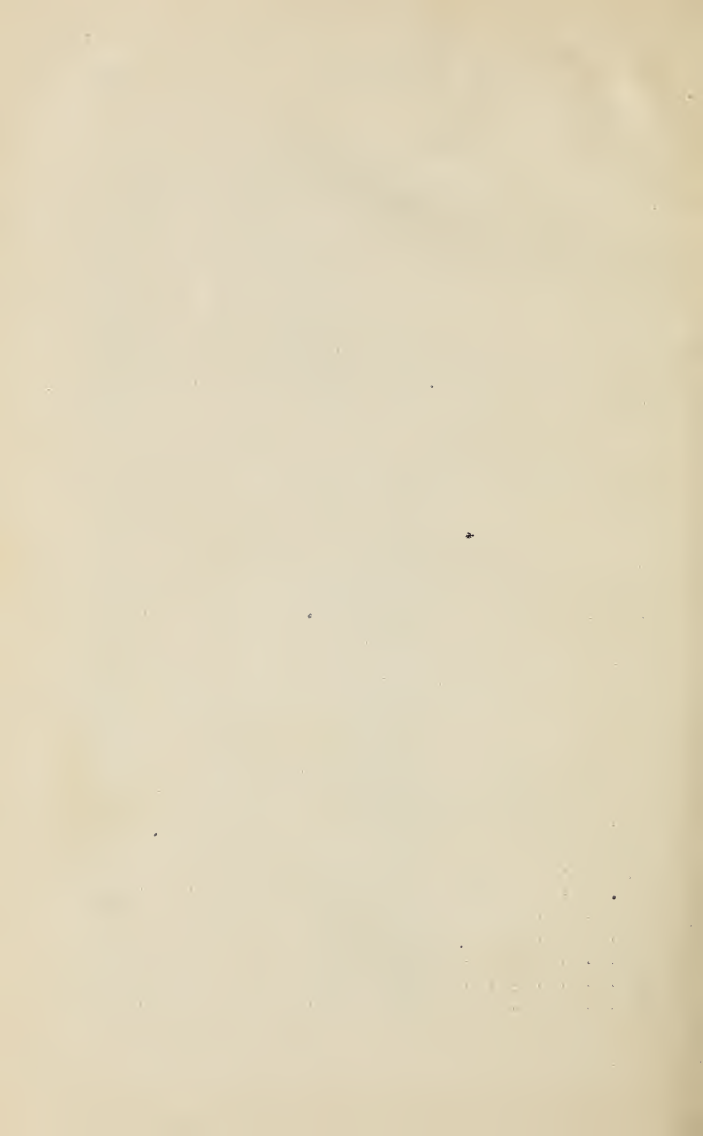
TABLE OF RESISTANCE OF WIRE

Chemically pure, 1 m. long, 1 mm. in diameter, at 0° C. (Jenkin),
RELATIVE RESISTANCES (Ayrton)

		Relative Resistances
Silver, annealed	0.01937 ohm	1.000
Copper, annealed	0.02104 "	1.086
Zinc	0.07244 "	3.741
Platinum	0.11660 "	6.022
Iron, annealed	0.12510 "	6.460
Lead	0.25270 "	13.050
German silver	0.26950 "	13.920

VALUE IN MILLIMETERS OF BROWN & SHARPE WIRE-
GAUGE NUMBERS

Number	Diameter mm.	Number	Diameter mm.
1	7.348	21	0.723
2	6.544	22	0.644
3	5.827	23	0.573
4	5.189	24	0.511
5	4.621	25	0.455
6	4.115	26	0.405
7	3.656	27	0.361
8	3.264	28	0.321
9	2.906	29	0.286
10	2.582	30	0.255
11	2.305	31	0.227
12	2.053	32	0.202
13	1.828	33	0.180
14	1.628	34	0.160
15	1.459	35	0.143
16	1.291	36	0.127
17	1.150	37	0.113
18	1.024	38	0.101
19	0.912	39	0.090
20	0.812	40	0.080



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105,

$C = \frac{L - L_1}{L_2 - L_1}$
 $1.4 = \frac{L - 10}{20 - 10}$

Exercise Page 164

L is x inside temperature
 then $70 - x$ degrees no. of degrees water
 falls

$2(70 - x)$ units no. of calories of heat
 given off.

Rise in temperature of water = x°
 no. of cal. of heat consumed = $.5x$

" " " " in melting ice = 40
 total amt of heat consumed = $40 + .5x$

$$\begin{aligned}
 \therefore 40 + .5x &= 2(70 - x) \\
 2.5x &= 100 \\
 x &= 40
 \end{aligned}$$

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